Enterprise Mobile Infrastructure 2017

Mobile Experts

Abstract:

This report provides a view of how eight different vertical markets will invest in mobile infrastructure. We highlight the trend away from DAS toward Small Cells, DRS, CBRS, and repeaters as low-cost options. This analysis provides detailed cost analysis on each technology choice for vertical market scenarios in stadiums, hotels, hospitals, retail, corporate, and other vertical markets.

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1 EXECUTIVE SUMMARY

In last year's report, Mobile Experts estimated the "value of wireless" to both mobile operators and enterprises in various in-building vertical segments including stadiums, hotels, hi-rise office buildings, hospitals, etc. The analysis showed that the value of wireless is generally far higher for enterprises than for mobile operators. Not surprisingly, mobile operators are increasingly less inclined to invest in in-building wireless projects, while enterprises are more so. With the exceptions of some marquee public venues like stadiums and airports, operators do not see good return on investment in many enterprise venues. Meanwhile, enterprises see increasing utility and value of seamless mobile services indoors and are ready to spend on mobile infrastructure equipment, and they are seeking right solutions.

As the in-building market transitions from the top end of the market (i.e., stadiums and airports) to smaller venues across diverse vertical segments, the traditional in-building market segments of DAS vs. Small Cells vs. Repeaters are evolving traditional product lines, expanding distribution partnerships, and honing market focus to address larger pools of smaller venue/dollar projects.

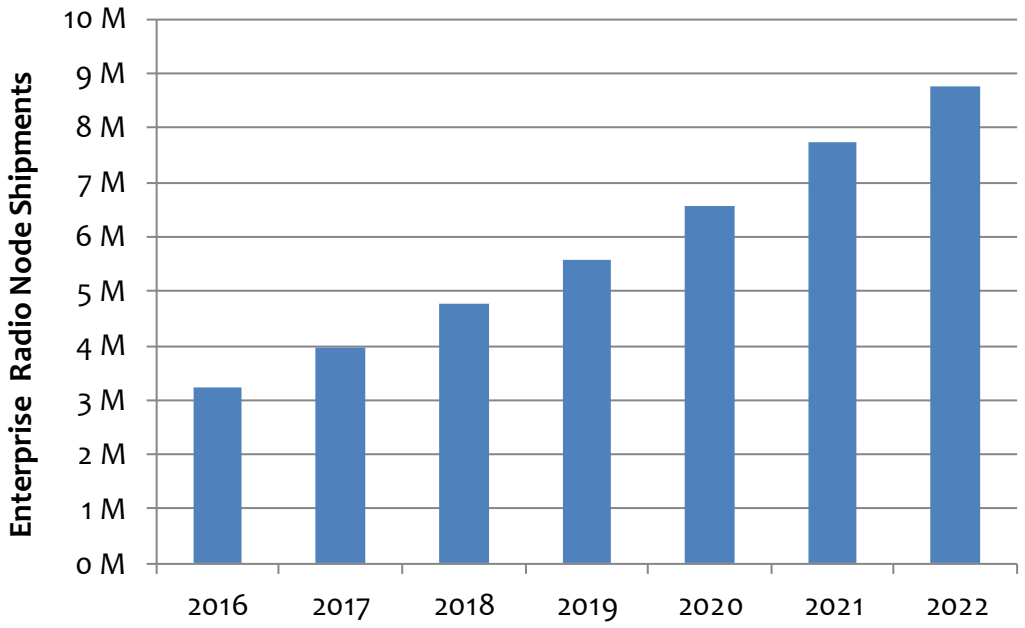
- DAS vendors are moving "down market" by introducing lower-cost solutions, e.g., "Embedded DAS" for smaller venue projects.
- Meanwhile, some repeater vendors are retrofitting repeaters with small cells to target larger and more urban venues.
- Small Cell vendors, meanwhile, are targeting tech-savvy enterprise segments, and operators, that require good visibility into traffic profiles to enable value-added applications, or improve cell-edge performance through eICIC and CoMP.
- As the top end of the enterprise mobile infrastructure market gets saturated, vendors are converging towards hybridized solutions that target specific cost-performance requirements of individual enterprises and vertical segments.

One of the biggest short-comings of Small Cells has been its limitation as a single-operator solution that prevents widespread enterprise adoption. CBRS promises to deliver a multi-operator small cell solution with Wi-Fi-like simplicity and relatively low cost profile. With an implicit support[1] of all major operators in the United States, CBRS has the potential to disrupt the in-building wireless space in its biggest market. Based on cost and deployment profiles of CBRS Small Cells and evaluation of in-building vertical segments, Mobile Experts predicts that CBRS Small Cells will be most appealing to the Hotel, Commercial Building, Hospital, Corporate and College Campus, and Retail Mall segments. Moreover, we expect the target addressable market for CBRS Small Cells in the United States is over 11 billion square feet of commercial space across 56,000 buildings. It is our expectation that the gradual "seeding" of CBRS devices will favor mainstream enterprise adoption of CBRS Small

[1] All four major operators in the United States have joined the CBRS Alliance. This implicit endorsement indicates operators' interest in promoting the CBRS ecosystem and pushing for device support of this band.

Cells to solve in-building wireless challenges that many enterprises face today, and more in the future.

Despite the challenges of complex business models that hinder direct enterprise deployment of in-building wireless solutions, the market continues to grow. The latent demand for seamless mobile coverage and capacity indoors exists in many existing premises, and key stakeholders in new construction projects are more cognizant of the need for good mobile services indoors. In turn, enterprises are increasingly funding in-building wireless projects themselves.



Source: Mobile Experts LLC

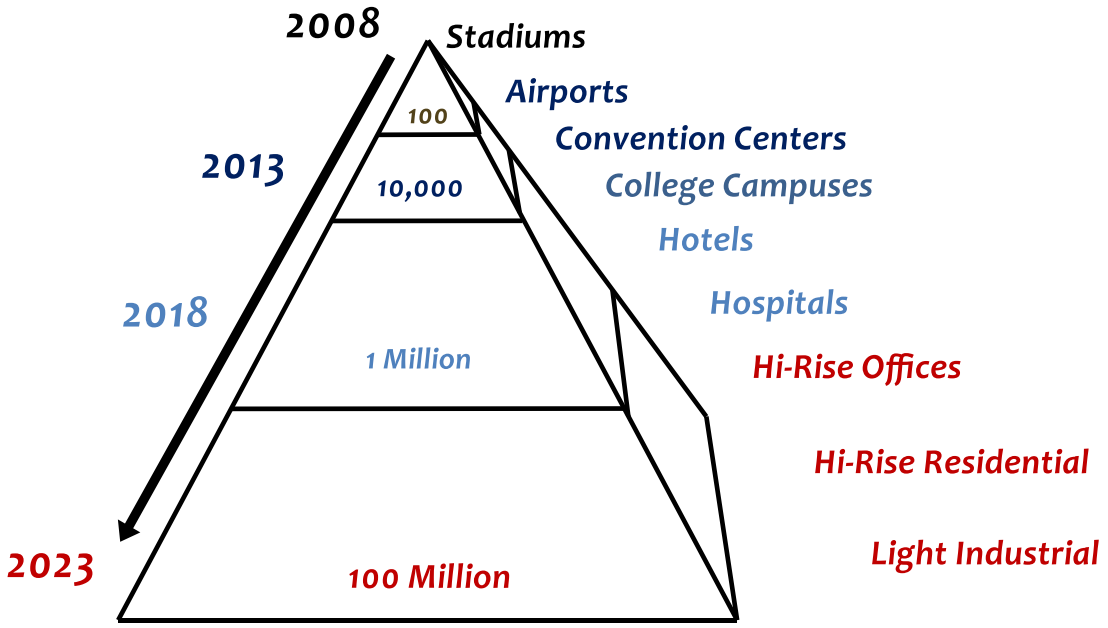
Chart 1: Growth of Enterprise Mobile Infrastructure, 2016-2022

Mobile Experts expects the Enterprise Mobile Infrastructure equipment market will grow at 18% CAGR from roughly 3.2M radio node shipments in 2016 to over 8.7M units by 2022. The biggest growth is expected to come from the Small Cells category, more specifically DRS units such as Ericsson Radio Dot and Huawei's LampSite, which is expected to grow quickly at about 30% CAGR from 2016 to 2022. North America remains the largest market for the enterprise mobile infrastructure equipment with mature ecosystem of system integrators and infrastructure vendors. In China and APAC, the business model is different but we will see strong growth, primarily from strong adoption of RRH and DRS radio nodes deployed by operators for enterprise indoor applications.

In revenue terms, the market will grow from over $2.4B in 2016 to over $3.6B in 2022. While still growing at a low single-digit percentage, the DAS segment is expected to fall from almost 70% of the total Enterprise Mobile Infrastructure equipment revenue in 2016 to 50% in 2022. Meanwhile, the Small Cells revenue share will increase from 20% in 2016 to 31% in 2022. The Repeater revenue share is expected to grow from 11% in 2016 to 19% in 2022 as the market transitions to serving smaller enterprises and venues.

2 ENTERPRISE MOBILE INFRASTRUCTURE MARKET OVERVIEW

Enterprises have been frustrated by poor indoor coverage for years. Although mobile operators have been investing tens of billions of dollars in capital expenditure each year, indoor mobile coverage and data performance have been poor in many buildings. Most of the operator's capital is spent upgrading the macro network to keep up with increasing subscriber demand. The mobile operators' macro-first network investment philosophy has oftentimes left indoor coverage issues to be resolved later, more or less, to be figured out by enterprises.



Source: Mobile Experts

Figure 1. Illustration of Enterprise In-Building Market Trend

For the past several years, Mobile Experts has been using the diagram above to illustrate the migration of in-building market trend from large venues like stadiums to smaller commercial buildings. The timing that we predicted in 2011 still seems about right. In North America, where the enterprise mobile infrastructure market is the largest and most mature, most major stadiums and airports have been built out already. While new construction continues to fuel this top end of the market, the overall market trend is moving downward to smaller venues like hotels, hospitals, high-rise commercial buildings and higher education campuses.

Wi-Fi, Plus Mobile

Wi-Fi has always been a "work horse" for indoor wireless data. In fact, Wi-Fi is on the path to bring even faster (theoretical peak) data rates and better user experience in the forthcoming 802.11ax standard. Chipsets are already sampling, and we expect to see early products coming to market in late 2017. Mobile Experts expects enterprise-class access points and client devices to ramp in 2018. While the Wi-Fi technology continues to bring faster-speed devices and network products, it has not been reliable enough to be a sole in-building network for *all* services. While non-realtime applications like email, browsing, and streaming can be accomplished on 'spotty' wireless networks, a latency-sensitive application like voice calling requires a consistent and reliable wireless link. As a contention-based technology, Wi-Fi has a fundamental disadvantage compared with fully controlled technology like LTE. For Wi-Fi, especially when many users are contending to get access to a finite spectrum resource, the wireless link quality cannot be guaranteed. For this and other convenience reasons, Wi-Fi calling has not replaced seamless mobile phone calling.

IT experts in all vertical markets are very familiar with Wi-Fi, and have a clear understanding of its drawbacks in terms of fading issues, dead spots, and congestion with too many access points in competition for a limited spectrum bandwidth. Two of the biggest weaknesses for Wi-Fi are:

1) uncoordinated access for spectrum which becomes problematic in highly congested environment with large numbers of access points and client devices contending for spectrum; and,
2) lack of seamless authentication that requires users to authenticate via portal or certificate-based authentication.

These obstacles have largely made Wi-Fi calling less appealing than cellular based voice services which provides seamless authentication and mobility in and out of buildings.

From a consumer's perspective, these technical limitations translate to unreliable or cumbersome technology for making simple voice calls. When a consumer must authenticate to a Wi-Fi network, via username/password for example, before making a phone call, checking email, or tapping on a mobile app, the technology has already become useless for that end user. For phone calls using Wi-Fi Calling, the underlying Wi-Fi network quality needs to be consistent and throughput good enough to not drop too many packets to be noticeable by the user. As an uncoordinated system needing to share unlicensed spectrum, the system cannot coordinate and avoid contention when some other Wi-Fi devices decide to get online. While Wi-Fi Calling has been disruptive force in the market, it has not replaced the need for mobile infrastructure for enterprises looking to provide seamless voice services indoors.

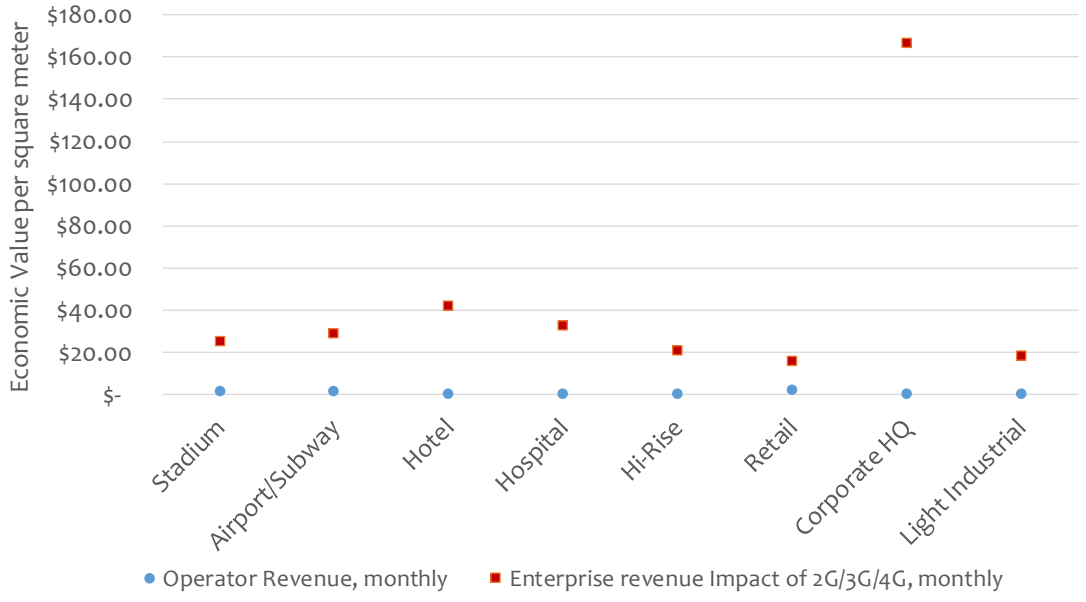
Mobile Experts has clearly noted a strong preference for both cellular (3G/LTE) and Wi-Fi networks at various enterprises. Many tech-savvy enterprises understand that Wi-Fi offers a good, inexpensive solution for wireless data connectivity, but a separate mobile

infrastructure is needed to handle seamless voice and cellular data experiences that their customers and workers expect inside their buildings.

The overall LTE signaling and control system is superior to Wi-Fi, with more robust link budgets for control channels and a more highly coordinated system to handle interference between indoor and outdoor networks. LTE operators have been more successful in placing infrastructure in the field which truly supports consistent high data rates. Tight coordination across macro base stations and small cells to avoid or minimize interference (thus impacting average user throughput) has served the cellular/LTE community well. A careful engineering and coordination of macro and in-building mobile infrastructures will remain a sustainable advantage over Wi-Fi for a foreseeable future.

High Value of In-Building Wireless for Enterprises

In last year's report, we analyzed the value of in-building wireless from perspectives of a mobile operator and an enterprise across different vertical sectors. Mobile Experts found that seamless wireless connectivity has big economic impact to enterprises in terms of customer value, worker productivity, and property asset value. (For the details on the *value of wireless* calculation across the different verticals, please refer to Mobile Experts' *Enterprise Mobile Infrastructure 2016* report.)



Source: Mobile Experts

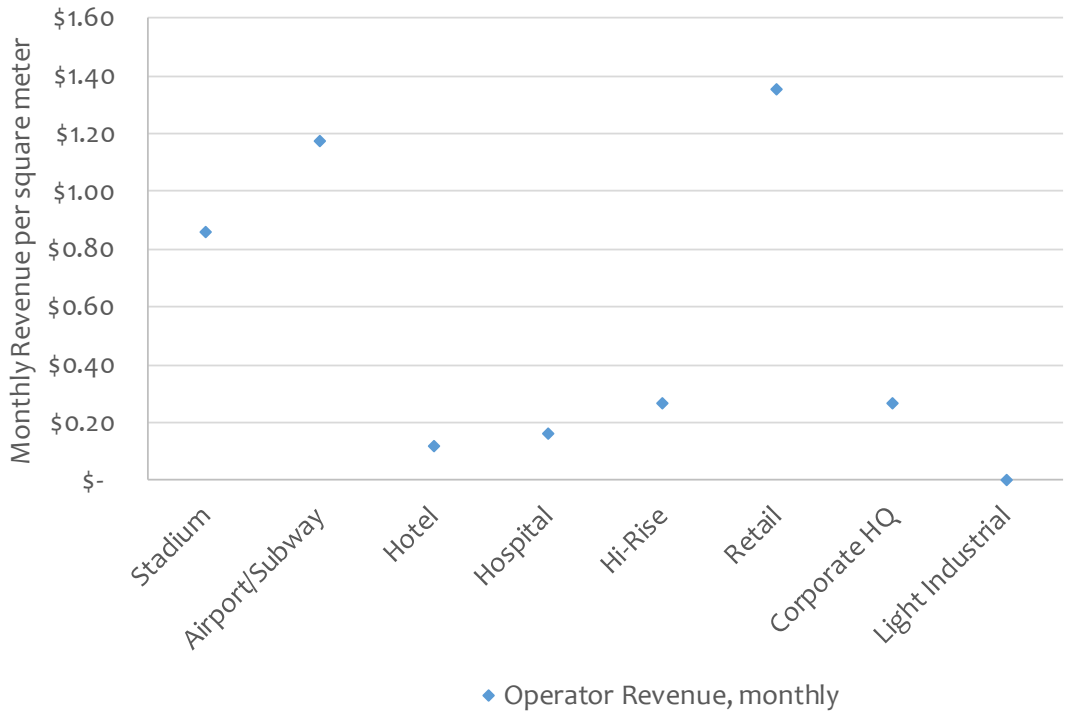
Figure 2. Value of Wireless Coverage across Vertical Industries

As shown above, enterprises clearly reap greater value from seamless mobile coverage indoors than mobile operators. Mobile services are increasingly seen as essential to many enterprises. Each vertical market is different, but there is clear evidence that a building owner's success relies on good mobile coverage indoors. For example, hotel managers report that conference organizers and big corporate clients insist on strong mobile services at their properties. In another example, a UK hospital is requiring mobile services indoors to accommodate doctors and hospital staff who increasingly rely on their smartphones and text messaging for critical work communications. Moreover, some high-end commercial landowners report that having robust mobile coverage enhances the appeal of a property to prospective buyers and tenants. With more and more people cutting landline phones permanently, mobile phone usage at homes and workplaces are becoming essential for many people, and good mobile coverage, especially at high-end properties, is simply expected.

For some remote enterprises such as mining camps, oil rigs, and large farms, mobile technology is replacing two-way radios for basic voice and other critical communications. As these remote businesses increasingly adopt mainstream mobile technology such as smartphones and other gadgets, sharing data is becoming more prevalent as well. For some, IoT applications are also rising in use with data collection and control systems via mobile devices and applications. With more and more enterprise services get online, criticality and importance of in-building wireless networks and services are likely to increase.

In-Building ROI Not Compelling for Operators

While enterprises see increasing utility and value from good mobile services indoors or some remote places, mobile operators are less inclined to deal with hundreds and thousands of potential in-building projects. For mobile operators, there's just not enough revenue opportunity to justify investments in most buildings. Besides high-density venues like stadiums, airports, and possibly large retail malls, most other vertical industry premises only account for about $0.20 per square meter or $0.02 per square foot. That's a tiny sum compared to $1-$2 per square foot required to put a Small Cell or light DAS system in place.



Source: Mobile Experts

Figure 3. Mobile Operator Revenue Opportunity across Different Venues

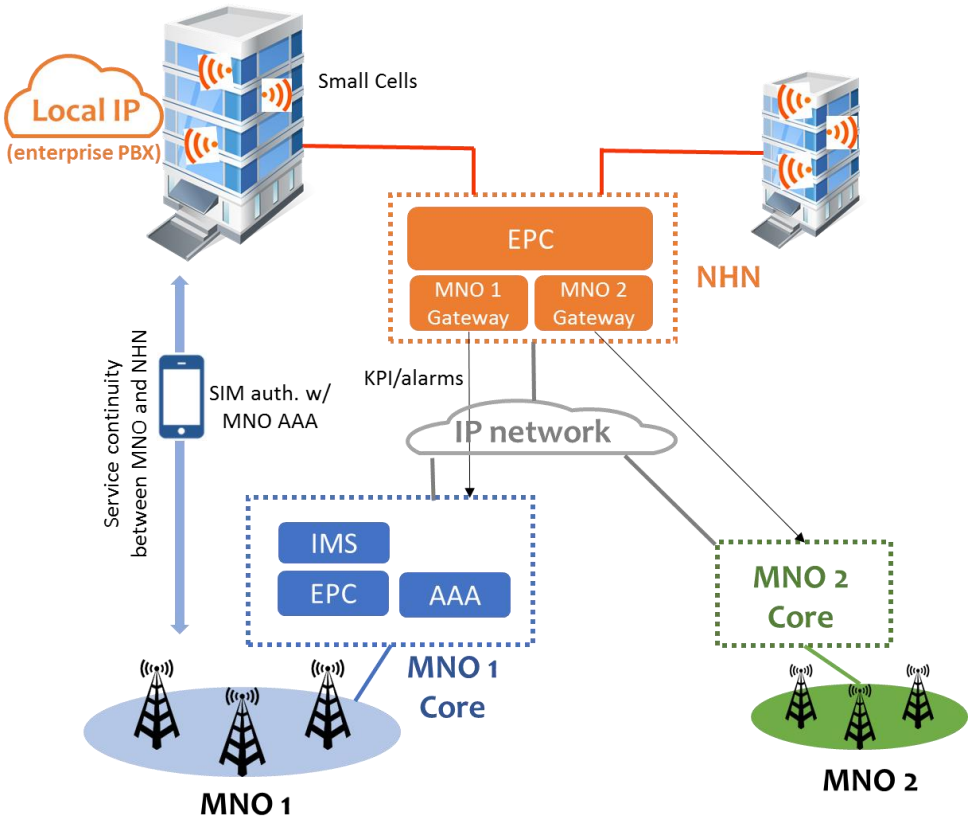
A mobile operator's hope is that low-band signals from outside macro sites can penetrate enough to provide adequate customer experience indoors, and not get complaint calls.

Neutral Host Providers Needed

For seamless mobile user experience, coordination of networks inside and outside the building is key. Moreover, for many smaller enterprises with limited telecom expertise and budget, managed services may be the only viable means to achieve mobile coverage service through a shared mobile infrastructure system. To serve this need, neutral host providers are critical stakeholders to make this a reality. The neutral host providers can serve as a knowledgeable intermediary between operators and enterprises to provision and manage in-building mobile services. Managed services through a neutral host network (NHN) provider requires integration of core networks between the NHN and multiple mobile operators to achieve seamless mobile services in and out of buildings.

The interworking between NHN and multiple mobile operators can leverage the WLAN internetworking architecture as defined in 3GPP. Here, a mobile device can use ePDG to gain access to mobile operator IP services, including voice services over IMS for example. The service continuity can be maintained between NHN and mobile operator network, and local IP services, such as enterprise PBX, can be provided through local breakout at the neutral host network. Another key aspect of the NHN core network is to provide KPI or

charging metrics to mobile operators through so-called MNO gateway, so that mobile operators can understand and manage how in-building mobile network may impact its macro networks outside.



Source: Mobile Experts

Figure 4. Neutral Host Network (NHN) Provider Architecture

A managed service offering from a neutral host provider is a great match for CBRS Small Cells. Because CBRS radios operate in the "neutral" 3.5GHz spectrum band, presumably supported by all major operators, there is no need for close coordination with mobile operators in RF design. The CBRS Small Cells can be deployed by the neutral host provider or the enterprise themselves. CBRS allows the neutral host provider to independently deploy indoor LTE networks and support neutral hosting of multi-operator services without burdening mobile operators for each indoor deployment.

Simply, the neutral host managed services model provides benefits to all stakeholders involved. Enterprises can offload the complexity of building and managing mobile network services, including complex internetworking with mobile operator core networks for seamless services. In addition, the "as a service" model provides a known expense outlook, without the uncertainty of building and operating a network directly by the enteprise. For mobile operators, dealing with a fewer number of neutral host providers and their networks

is far more efficient than working with potentially thousands of enterprises directly, many of whom do not have telecom expertise. Enabling LTE network coverage indoors can benefit mobile operators' subscriber experience as well. Finally, for the neutral host providers, indoor network deployments can be independently led by themselves, third-party system integrators, or enterprises directly. This removes a huge barrier of working closely with mobile operators as in traditional small cell or DAS projects. This freedom to deploy without close coordination with mobile operators provides agility to quickly deploy and activate LTE services.

3 TECHNOLOGY OPTIONS

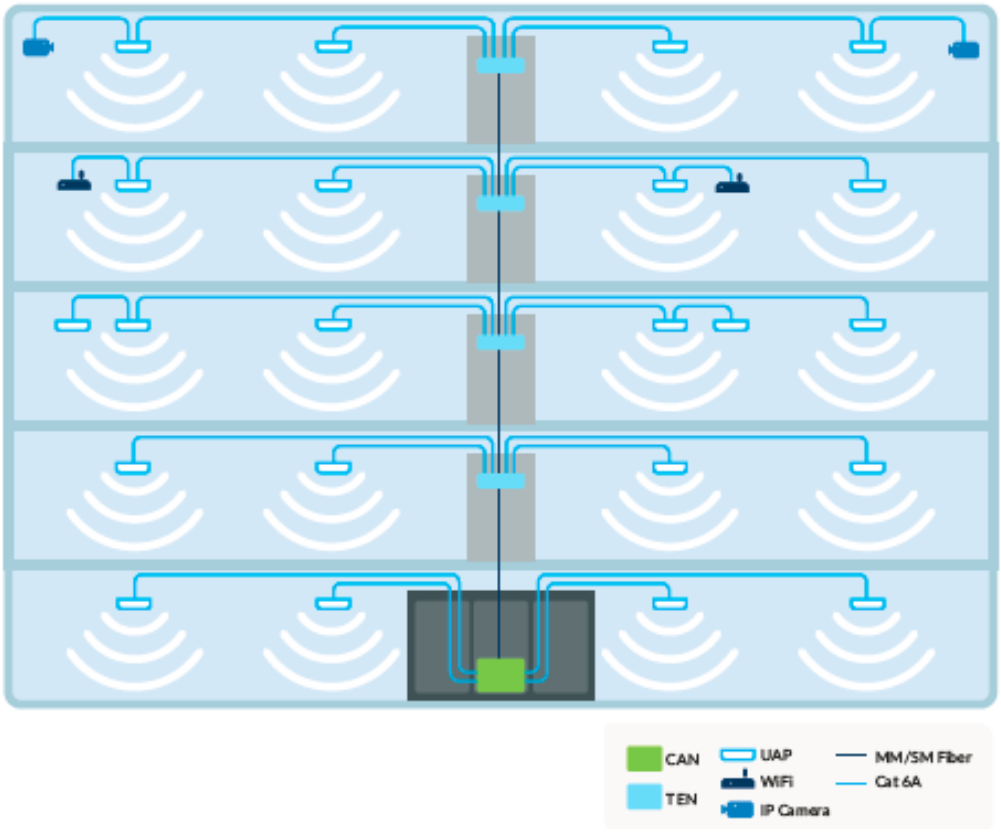
Most enterprises are unaware of the various technology options available for in-building mobile infrastructure. In fact, most projects today are executed without a careful review of what technology option provides best near-term and long-term solution for how mobile infrastructure should be provisioned based on usage. Because a typical enterprise does not know full alternatives available to it, in most cases, the first vendor to show up for a bid or project can sway which options to take. Generally, the in-building mobile infrastructure market has been broken into the following options, based on historical usage and applications:

- Distributed Antenna Systems (DAS) – for very large, high-traffic public venues
- Small Cells and RRH – for mid-size venues requiring scalable single-operator solution
- Repeaters – for small, low-traffic venues to simply extend coverage
- Wi-Fi - for wireless connectivity to the Internet, unreliable for seamless voice services

Distributed Antenna Systems (DAS)

A DAS system combines multiple radio signals, then distributes the signals to multiple antenna locations. A headend system effectively converts RF through IF down-conversion to an optical signal that is transported over a fiber optic cable to a remote unit, which converts it back to RF, amplified and transmitted via antenna. The RF-to-optical conversation provides better protection against passive intermodulation (PIM) interference, found in old Passive DAS systems. Hence, most large DAS projects involving multi-operator, multiple frequency bands typically deploy Active DAS architecture as shown below.

A typical DAS system today does not include a signal source, so a DAS project typically involves procurement and installation of the DAS, followed by installation of a signal source for each mobile operator. While traditional DAS projects covering very large venues like NFL stadiums need macro base stations as signal source for heavy capacity handling, some smaller DAS projects have started to use small cells as a signal source to remove unnecessary complexity in the system design and also to reduce the overall cost.



Source: Commscope

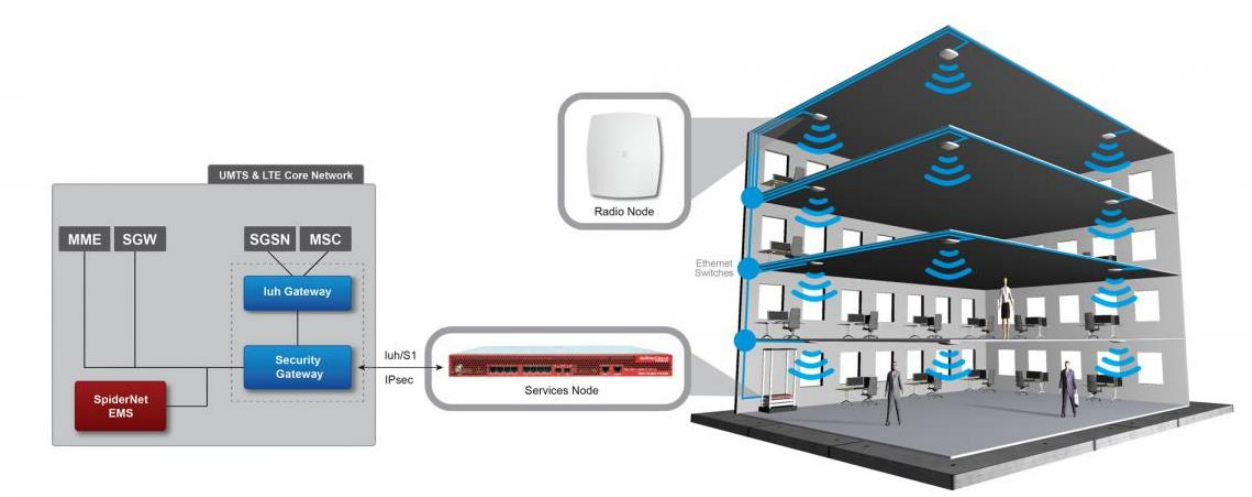
Figure 5. Typical DAS Architecture

For enterprises, DAS projects can be frustrating and challenging, on top of being expensive. An enterprise can buy a DAS and install it anytime, but must also convince the mobile operators to support signal sources to feed the DAS system. Coordinating DAS projects with mobile operators and securing backhaul for macro base station connectivity back to operators' core networks can be frustrating and uncertain at times. To remove some of these complexities, especially for smaller venue projects, future DAS products are likely to include the signal sources as a single integrated product solution so that enterprises can buy just one product to complete the project.

Small Cells and RRH

Small cells are becoming active extensions to macro networks. As mobile traffic usage continues to rise, operators are scaling their mobile networks at the "edge" to capture and deliver traffic where the users are. As an integrated system that delivers baseband processing necessary to create 3G/4G signal (and presumably 5G in the next few years) and radio components necessary to transmit and receive the signal locally, small cells offer scalable means to grow the radio network. In terms of indoor deployments, baseband and radio processing are typically handled locally on radio node units. For simplicity of

installation and to reduce cabling costs, most enterprise focused small cells use Ethernet cabling for transport and power via Power-over-Ethernet (PoE). Further, a centralized controller is often used for provisioning and aggregation of small cell radio nodes in a premise back to the mobile core network.



Source: SpiderCloud

Figure 6. Small Cell (RRH) Architecture

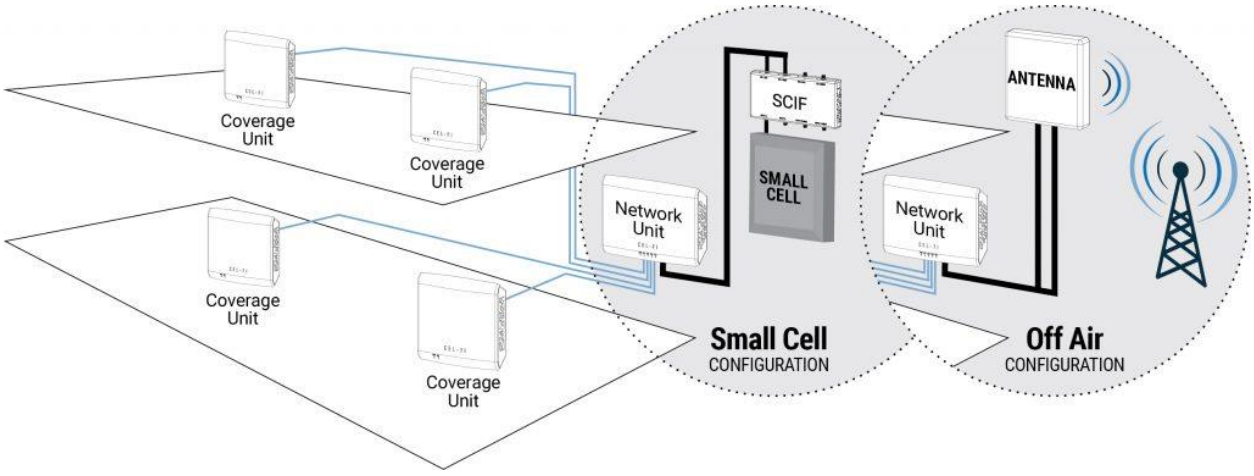
Today, Small Cells typically handle only one operator. It is possible to implement multi-operator coverage using small cells, using techniques to share resources at a radio level (MORAN) or at a core network level (MOCN). However, except for some parts of Europe, mobile operators generally do not support MORAN and MOCN because these approaches require them to give up control. More and more, small cells are being approved by mobile operators to be purchased by enterprises and system integrators so that the procurement and deployment process can be much more simplified without heavy mobile operator participation.

One of the interesting developments in the Enterprise Mobile Infrastructure space in the past year has been the development of CBRS ecosystem. Small Cells leveraging CBRS band (3.5GHz shared spectrum in the USA) can potentially fill a void in the marketplace between Wi-Fi and DAS. While Wi-Fi is considered inexpensive, it lacks in seamless mobile voice services. On the other hand, the multi-operator DAS solution is typically too expensive for many enterprises to consider, not to mention the difficulty of securing a signal source from the operators. CBRS small cells, with inherent multi-operator support and simplicity of Wi-Fi like installation, can provide a cost-effective mobile coverage solution for third-party neutral host providers and enterprises alike.

Repeaters

Repeaters are the simplest infrastructure to create mobile coverage. A repeater essentially boosts a signal to/from a nearby macro base station, extending the range of the outdoor network. Careful placement of the repeater's antennas can improve indoor coverage. The repeater's antenna can be placed nearby a window or on a rooftop to improve signal reception and re-transmission inside a building.

Repeaters are widely available, and recent products have been endorsed by mobile operators so that an enterprise can either directly buy the repeater from an operator or from a supplier. These "legal" repeater products generally handle the signals for a single operator. Hence, some deployments may require multiple repeater antennas to handle multi-operator coverage inside a building. To broaden the appeal of repeaters, some vendors have introduced products that take advantage of small cells as pre-integrated signal source to cover larger venues with higher traffic demand.



Source: Nextivity

Figure 7. Repeater Architecture (Off-Air or Small Cell-Powered)

Carrier Wi-Fi

While Wi-Fi provides cost-effective solution for enterprise wireless data needs, it has not completely fulfilled the enterprise desire to leverage it for both seamless voice and data services. While it provides low-cost solutions through tremendous global scale, Wi-Fi user experience has been frustratingly slow in dense environments due to congestion. More crucially, seamless device authentication has been a sore weakness in the Wi-Fi ecosystem for some time. For these reasons, Wi-Fi Calling has not completed removed the enterprise desire to invest in in-building mobile infrastructure to date.

The next-generation Wi-Fi technology, 802.11ax, introduces significant changes in the physical layer to improve the average user throughput in dense environments, a key deficiency often cited by end users of the Wi-Fi technology. Despite multi-gigabit peak speeds often touted, in reality, users experience frustratingly slow data rates when trying to access public Wi-Fi in dense environments like airports. In addition to this main objective, 802.11ax is expected to support higher data rates and improved channel access, utilizing similar underlying technologies used in LTE. These features in aggregate expect to improve average user throughput and improve the overall performance.

Unlike 802.11ac which operates strictly in the 5 GHz band, the 802.11ax operates in both 2.4 and 5GHz bands. More importantly, it significantly increases the number of subcarriers while preserving the existing channel bandwidth. Larger OFDM FFT sizes, narrower subcarrier spacing, and longer symbol time, in aggregate, improves robustness and efficiency while keeping the data rates same as the 802.11ac. In fact, with a higher modulation support for 1024 QAM, the 802.11ax provides a higher maximum data rate. More importantly though, it provides higher efficiency in multipath fading environments. With the higher number of subcarriers, the 802.11ax can more efficiently support simultaneous client devices by effectively divvying up the frequency.

Similar to 802.11ac, 802.11ax devices use explicit beamforming to direct data packets simultaneously to multiple users who are spatially separated. While the 802.11ac only defined MU-MIMO on the downlink, the 802.11ax standard defines uplink multiuser mode as well in which simultaneous data transmission from multiple client devices to an access point is possible. Another key addition of the 802.11ax standard is that it defines two different ways of multiplexing users: Multiuser MIMO (MU-MIMO) and Multiuser Orthogonal Frequency Division Multiple Access (MU-OFDMA). In essence, 802.11ax borrows the underlying OFDMA technology used in LTE base stations to centrally manage multiple client devices.

With a combination of downlink and uplink MU-MIMO and MU-OFDMA, the 802.11ax is expected to support four times the average user throughput. With combinations of these techniques and higher physical data rates, 802.11ax is expected to significantly improve user throughput especially in dense environments, which has been an Achilles' Heel for Wi-Fi in comparison to LTE. Note that even if one network of access points coordinates transmission for improved performance, Wi-Fi will always include contention between unrelated access points—Wi-Fi will never reach equal performance to LTE.

Effectively, the new Wi-Fi technology will improve the spectral efficiency of existing unlicensed bands. The question remains, how long can the 802.11ax spectral efficiency gains last before they get overcome by the increasing number of Wi-Fi and other unlicensed devices that flood the available spectrum. Without additional spectrum for Wi-Fi to proliferate, the average user throughput experience may degrade over time.

In-Building Product Features and Fit

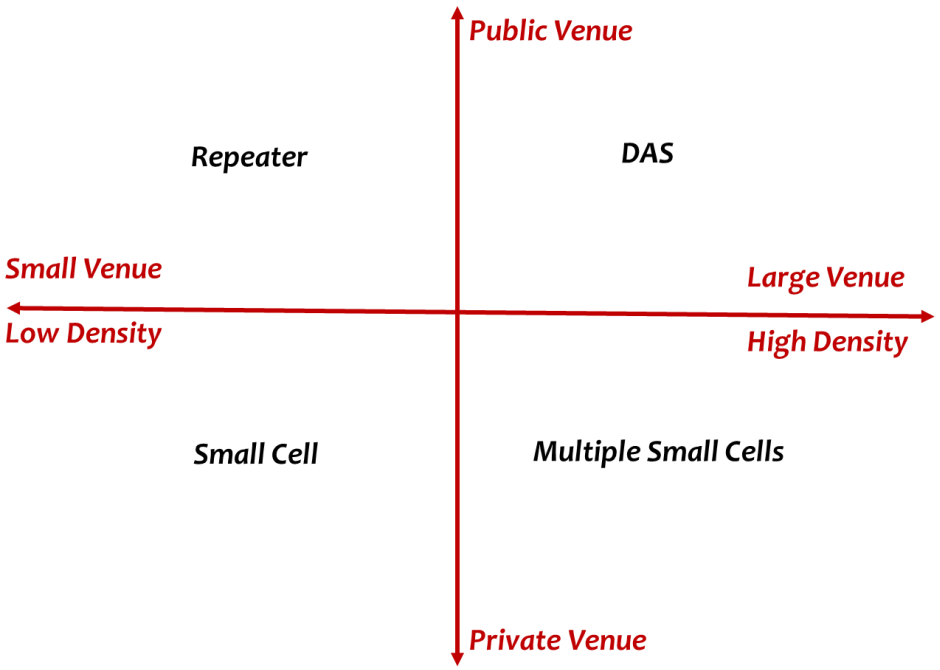
At a high level, DAS is a full-blown enterprise mobile infrastructure system with multi-operator, multi-frequency, and multi-technology features. It can be scaled and engineered to handle most challenging traffic density scenarios, but it comes with high installation and maintenance costs. Small Cells can offer highly scalable solution that can fit challenging environments as well, but lack the multi-operator feature required in public venue environments. Repeaters are inexpensive but limited to smaller venues with light traffic usage and mostly in suburban/rural areas. Lastly, Wi-Fi provides cost-effective solution for general wireless data usage, but as a "non-cellular" solution, lacks the fundamental mobile coverage (seamless voice) feature.

	Multi-Operator	Mobile Coverage	Capacity	Easy Deployment
DAS	✓	✓	✓	
Small Cell		✓	✓	✓
Repeater		✓		✓
W-Fi	✓		✓	✓

Source: Mobile Experts

Figure 8. Simple Comparison of Technology Choices and Features

Each in-building wireless product – i.e., DAS, Small Cell, Repeater, Wi-Fi – addresses different market segments based on product features and cost characteristics. While generally high-cost, DAS products are well suited for "public" venues requiring multi-operator support and the capability to handle very high traffic densities. For "private" venues like corporate office environment with workers on corporate service plans on a single carrier, small cells may provide cost-effective, scalable solution. For smaller venues that simply require "boosting" outside signal to improve cell coverage indoors, repeaters will likely be most cost-efficient solution.



Source: Mobile Experts

Figure 9. Market Fit for DAS, Small Cells, and Repeaters

Meanwhile, Wi-Fi is considered a good complementary solution applicable across all types of venues that require heavy wireless data access. It should be noted that for larger venues, a controller scheme is required for Wi-Fi to coordinate unlicensed spectrum usage across many access points. The user/data traffic density, size of venue, and multi-operator support requirements will largely drive what solution best fits the requirements of different enterprises.

Cost Optimization with Hybridized Systems

In-building wireless solutions have evolved over the past 20 years largely in isolation. DAS was developed for multi-operator scenarios from the beginning where outdoor bases stations were re-purposed for in-building usage. Small Cells were developed initially as an "in-fill" coverage solution, then evolved to meet growing data need in dense urban areas of the network. Repeaters were developed to help address weak signal inside buildings. Carrier Wi-Fi meanwhile avoided the use of licensed spectrum altogether to provide low-cost, high-capacity wireless LAN solution for enterprises. With widely different origins, each of these solutions is designed to be useful in different ways to address specific vertical market needs.

As the enterprise mobile infrastructure market ramps up, individual solutions may not solely meet an enterprise need perfectly. For example, a hotel may have low traffic usage in the

guest rooms, but high traffic density in the conference area. A major airport probably needs a high capacity, multiple operator solution in the common waiting area, but low-capacity, single operator coverage might be adequate in the baggage handling area.

As a result, the optimal solution for a building project may include elements of DAS, Small Cells, Wi-Fi, and/or Repeaters that are used in combinations. As illustrated in the figure below, possibilities include:

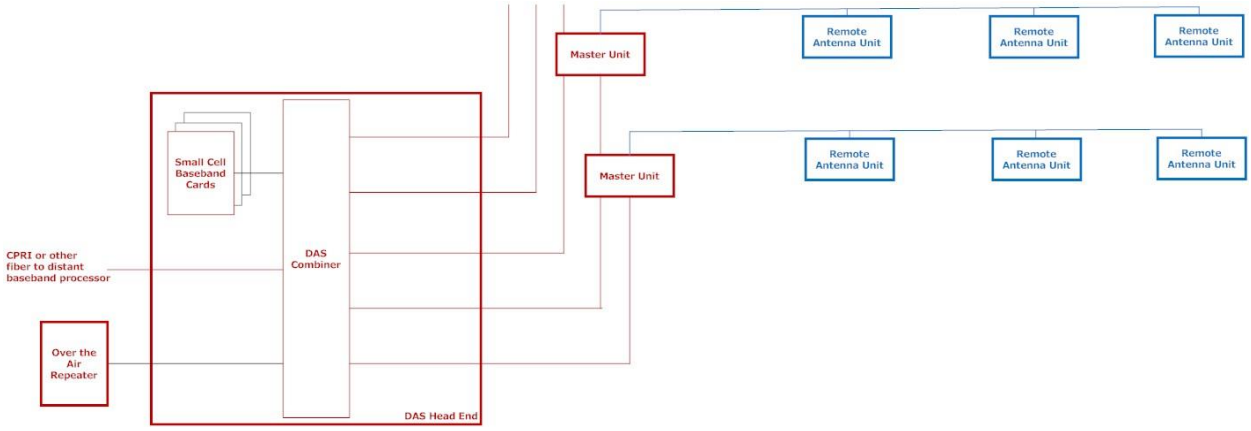
- Small Cells feeding DAS as a signal source: This combination happens routinely today, and will increase further over time to be adopted in majority of DAS projects. Small Cells are simply cheaper than macro base stations as a signal source. The next step in this evolution will be DAS systems with "embedded" small cells as the signal sources.

- Repeaters feeding DAS as a signal source: In cases where capacity and outdoor macro congestion are low, a repeater can be used to save cost and complexity. Use of a repeater simplifies the concept of "handover" from the outdoor network to the indoor DAS system, since the handset is not actually handing over from one baseband processor to another.

- Buildings can use a Light DAS system in one area, with a Heavy DAS system in another area. For example, one DAS sector may use multiple bands (for a crowded shopping area) with a single-band DAS sector to cover the parking structure.

- "Cloud RAN" architectures can be used to combine the distribution of a DAS network with advanced baseband processing. By pooling some of the baseband processing resources centrally, multiple buildings (or multiple areas within a building) can take advantage of LTE-Advanced features such as CoMP and eICIC, for ideal LTE operation.

- Remote Radio Heads and twisted-pair cabling to remote antenna units have been deployed in many cases, with products that are maturing quickly. These "Distributed Radio Systems" (DRS), which we count in the small cell category, offer full compatibility with macro handovers and other macro network features, for the most solid 3G/LTE links. In this case, CoMP and other LTE-A features can be implemented to utilize outdoor assets for performance improvement indoors.



Source: Mobile Experts

Figure 10. Hybridized In-Building Wireless System including DAS, Small Cells, Repeaters

As the market moves from a performance-first customer group (i.e., mobile operators) to a cost-sensitive customer group (i.e., enterprises), it's a classic case of "Crossing the Chasm" to the mainstream market. All the vendors working on the above technology alternatives are focused on cost reductions.

To be clear, the cost of the equipment itself needs to come down to overcome the "sticker shock" of initial capex cost. More importantly, the total cost of ownership, especially high installation and maintenance costs associated with in-building wireless projects must come down. Special attention must be paid to costs associated with installation, cabling, RF planning and design, and the overall provisioning, testing, and mobile operator approval processes.

It is interesting to note that mobile operators typically pay close attention to the unit economics of "cost per Gbps" since adding incremental capacity on top of broad coverage is a key driver of incremental capital expenditure and spectrum expenses. However, for many enterprises, they are more eager to understand and bring down the 'cost per square foot' metric now as the primary driver for in-building mobile infrastructure initially is to bring mobile coverage indoors. Here, the important factors are the equipment cost, cabling cost, installation cost, and other support costs which are needed to complete a project.

All the vendors---regardless of their technology prejudices---are moving in the same direction: Minimize installation and cabling cost, adding value in the equipment itself to simplify the process of deployment and maintenance for enterprises, but also to mobile operators. Here are some ways that suppliers are tackling the "cost challenge":

- "Full" DAS to "Light" DAS: For low-capacity buildings, system integrators and vendors are moving to "light" DAS design to minimize the number of bands to minimize system features and lower cost. Using a single band for each operator, or

using repeaters as signal source to minimize macro base station cost can bring down the overall project costs. In some cases, small cells are used as signal source (what Mobile Experts sometimes refers to as "Embedded DAS") to significantly bring down the cost per square foot. In some cases, high-power remote units are used for low-density venues to reduce the number of remote units in a project.

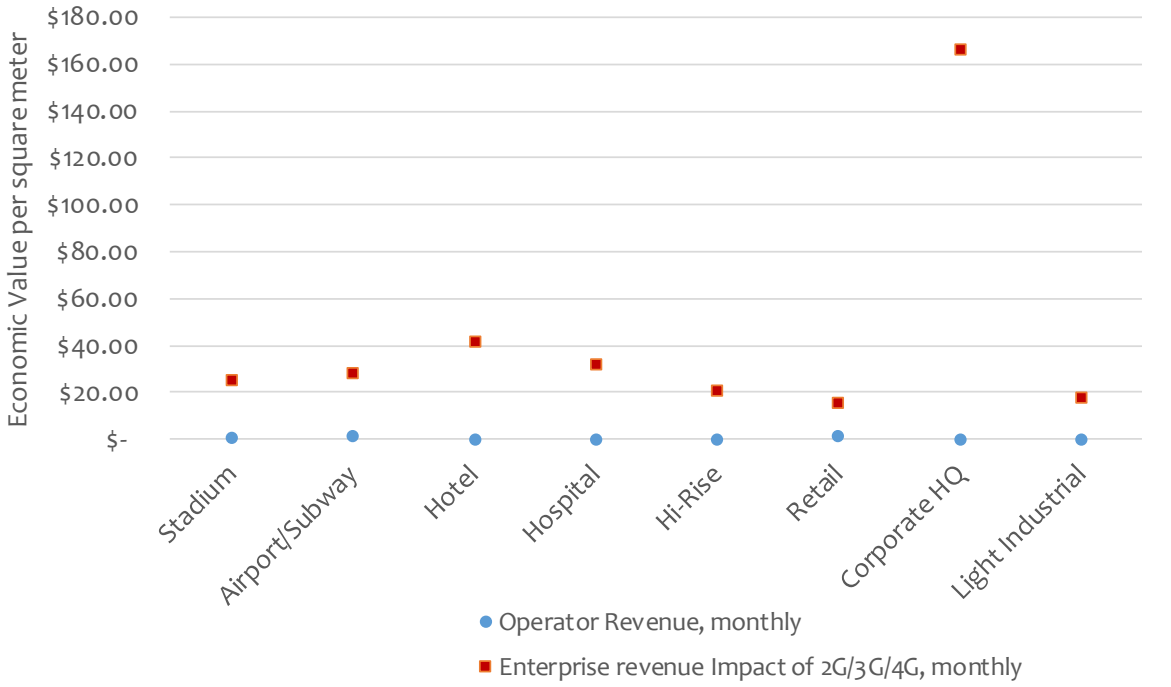
- Some DAS solutions use twisted-pair cabling to simplify the installation process and reduce the need for permits and licensed technicians. With installation of conduits, fiber optic and coaxial cabling costs representing 40-50% of installed DAS cost, the move to Cat-5/e cable can bring the labor cost down dramatically.

- Some repeater vendors are introducing hybridized active DAS/repeater solutions that can effectively expand the addressable market for repeaters to larger venues (<200K square foot) by using small cells as signal source of repeaters inside a building.

Infrastructure vendors and system integrators are getting creative in devising solutions with feature and sometimes product elements of DAS, small cells, and repeaters to optimize cost-performance requirements of varying in-building projects. Mobile Experts expects this trend to result in convergence of product features and some mergers among product vendors and system integrators in the next few years.

4 COST COMPARISON OF IN-BUILDING WIRELESS PRODUCTS

In last year's report, Mobile Experts explored mobile traffic profiles and business models of vertical industries to determine the 'value of wireless' to enterprises and to operators. In short, our analysis shows that the cost of mobile infrastructure is far more valuable to enterprises than the mobile operators as shown below. The bottom line is that enterprises will pay for mobile infrastructure, and mobile operators will be hesitant to fund in-building wireless projects outside of marquee venues. Economic cost is not the problem---instead, the problem lies in mobile solutions value chain where it is still complex for enterprises to simply buy and install mobile infrastructure products like Wi-Fi.



Source: Mobile Experts

Chart 2: Operator vs. Enterprise Value of Mobile Wireless

In this year's report, we take a closer look at the *cost per square foot* metric across the different in-building wireless solutions to see how much each solution costs in specific vertical markets. We fully acknowledge that each enterprise case may come to a different choice and decision in choosing one solution over another. Our exercise here is meant to quantify cost differential between solutions to see how certain price-sensitive verticals may view a solution like DAS or Small Cell over Carrier Wi-Fi, not to be prescriptive.

Coverage Costs ($ per square foot)

In our comparative cost analysis, we estimate average venue traffic profiles such as user density and traffic usage, as well as estimates of radio and networking equipment, along with labor installation costs and on-going operational expenses related to maintenance, power, and backhaul. We take 8-year NPV to arrive at the total cost of ownership for each vertical market across the different in-building solutions. We assume three operator support in our analysis.

Below is a summary of 'cost per square foot' profile of the different in-building technology/product choices across average vertical industry venue/traffic profile. It is generally clear that DAS is expensive and repeater and Wi-Fi are cheaper alternatives. As will be discussed in the next section, cost is not the only factor driving vertical enterprise decision. This cost comparison simply provides a general guideline of how an enterprise may factor in cost consideration in assessing multiple solutions that exist in the marketplace. It should be noted that the Repeater analysis was conducted only for the likely scenarios of smaller hotel and light industrial use cases as other segments are simply too large for repeaters to be effective or allowed by the mobile operators.

	Size (sq.ft.)	DAS	DRS / RRH	Small Cell	CBRS	Repeater	Wi-Fi
Stadium	2,000,000	$3.01	$2.48	$1.98	$1.16	$-	$0.91
Airport / Subway	630,000	$2.88	$2.42	$2.13	$1.17	$-	$0.84
Hotel	150,000	$3.57	$2.32	$1.74	$0.96	$0.27	$0.67
Hospital	300,000	$3.27	$2.38	$1.96	$1.24	$-	$0.69
Hi-rise Office	500,000	$2.62	$2.31	$1.89	$1.01	$-	$0.62
Retail Mall	900,000	$2.19	$2.27	$1.88	$0.98	$-	$0.59
Corp. HQ / Campus	1,000,000	$2.14	$2.27	$1.85	$0.97	$-	$0.58
Light Industrial	200,000	$3.80	$2.42	$1.73	$1.03	$0.22	$0.73

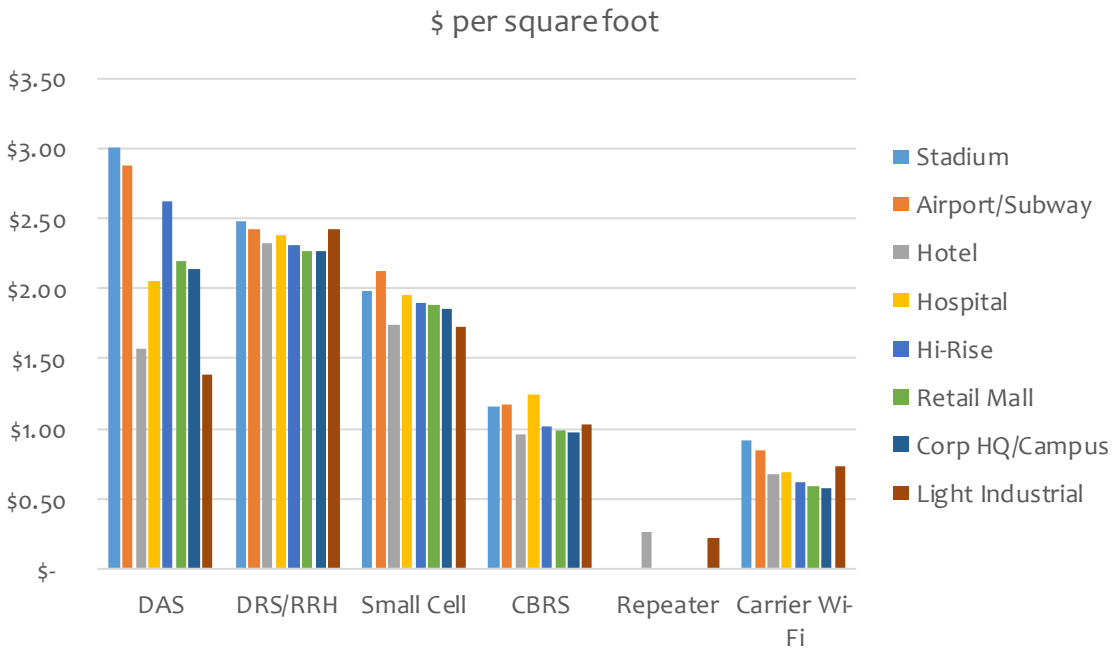
Source: Mobile Experts

Note: 8-year NPV of total cost of ownership including capex and on-going opex excluding operational expenses related to network management. Cost analysis based on three operator support.

Figure 11. Comparative Coverage Costs across In-Building Verticals

It is clear that DAS is generally more expensive than other product options, in terms of the *coverage* cost ($ per square foot). It should be noted that a large portion of this cost is due to high cabling and labor costs associated with DAS installations. Traditional licensed Small Cells offer a cheaper alternative, but they are limited by the single-operator nature of the product which limits its appeal in public spaces such as hotels. Repeaters offer a very low-cost alternative, but they are limited to small venue that do not require separate capacity handling. Wi-Fi offers a low-cost way to provide both coverage and capacity, but it does not

provide reliable and consistent wireless connectivity needed for seamless mobile voice service. CBRS small cells, though higher cost than Wi-Fi, has the potential to LTE services on Wi-Fi like infrastructure.

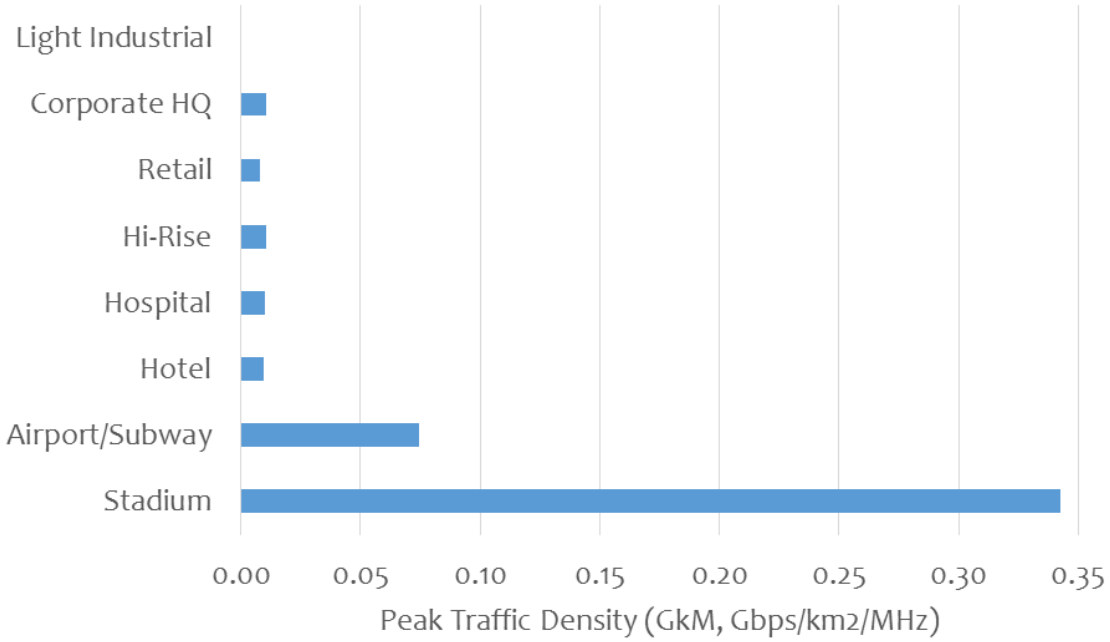


Source: Mobile Experts

Note: 'Full' DAS projects including large deployments leverage base station. Smaller 'light' DAS projects leverage small cells and sometimes repeaters to reduce the overall project costs.

Figure 12. Cost per Square Foot by Product Type

Even though DAS costs more, in terms of coverage cost, its cost profile may be more favorable in terms of the *capacity* cost ($ per Gbps) for venue with very high traffic densities such as major stadiums and airports as highlighted below. Although we have not specifically quantified the capacity cost in this report, it is reasonable to expect that enterprise or venue owners would opt for a flexible DAS platform that can scale capacity across multiple operators, multiple air interfaces, and multiple frequency bands once the DAS infrastructure is in place rather than deploying multiple, separate small cell/DRS/RRH networks every time a new operator is added or additional frequency bands are added to augment capacity.



Source: Mobile Experts

Figure 13. Traffic Density Profile across Vertical Segments

ROI Breakeven

Considering relative value of wireless to an average enterprise in each vertical segment, we have calculated how many months would be required for the enterprise to breakeven on the 8-year NPV value of installation and yearly operations. As detailed in last year's report, the value of wireless for the enterprises is high (since consumers and workers generally value mobile connectivity and use more of it). Because of this trend, the mobile infrastructure investments can be recouped in 1 or 2 months of use. Mobile infrastructure investment for most enterprises is a "no brainer".

	Size (sq.ft.)	DAS	DRS / RRH	Small Cell	CBRS	Repeater	Wi-Fi
Stadium	2,000,000	1.0	0.8	0.6	0.4	-	0.3
Airport / Subway	630,000	1.0	0.8	0.7	0.4	-	0.3
Hotel	150,000	0.7	0.4	0.3	0.2	0.0	0.1
Hospital	300,000	1.0	0.8	0.6	0.4	-	0.2
Hi-rise Office	500,000	1.3	1.1	0.9	0.5	-	0.3
Retail Mall	900,000	1.4	1.4	1.2	0.6	-	0.4
Corp. HQ / Campus	1,000,000	0.1	0.1	0.1	0.0	-	0.0
Light Industrial	200,000	0.6	0.4	0.3	0.2	0.0	0.1

Source: Mobile Experts

Figure 14. ROI Breakeven (in Months) for Enterprise

For mobile operators, the story is quite the opposite. Based on current business model of subscription services and relatively sparse usage of select in-building infrastructure systems, it would take mobile operators many more months to breakeven. For relatively large DAS investment, the breakeven period could range from 16 months for retail mall case to over 1.5M months in the case of light industrial use case. Obviously putting in place DAS for lightly trafficked industrial warehouse complex would be an overkill. For operators, placing inexpensive CBRS small cells to cover large retail mall or airports may make sense.

	Size (sq.ft.)	DAS	DRS / RRH	Small Cell	CBRS	Repeater	Wi-Fi
Stadium	2,000,000	35	29	23	13	-	11
Airport / Subway	630,000	25	21	18	10	-	7
Hotel	150,000	305	198	149	82	23	58
Hospital	300,000	202	147	121	77	-	43
Hi-rise Office	500,000	98	87	71	38	-	23
Retail Mall	900,000	16	17	14	7	-	4
Corp. HQ / Campus	1,000,000	80	85	69	36	-	22
Light Industrial	200,000	1,598,331	1,017,420	726,620	434,283	93,900	308,671

Source: Mobile Experts

Figure 15. ROI Breakeven (in Months) for Mobile Operator

Stadiums

Key assumptions about equipment and labor costs, traffic profile, and value of wireless to an operator and an enterprise (stadium venue owner or sports franchise) are shown below:

		DAS	DRS/RRH	Lic. Small Cell	CBRS Small Cell	Repeater	Carrier Wi-Fi
Venue & Traffic Profile							
	Venue size (sq. ft.)	2,000,000	2,000,000	2,000,000	2,000,000		2,000,000
	Mobile operators supported	3	3	3	3		3
	User density (user/sq.ft.)	0.0001	0.0001	0.0001	0.0001		0.0001
	Coverage per radio node (sq.ft./radio)	60,000	10,000	10,000	10,000		5,000
	Total users (peak)	78,571	78,571	78,571	78,571	78,571	78,571
	Bandwidth (Mbps, peak)	9,586	9,586	9,586	9,586	9,586	9,586
	Total Radio units	**100**	**1,200**	**600**	**200**		**400**
	Cabling (ft)	7,071	24,495	17,321	10,000		14,142
Capex & Opex Costs							
	Radio unit cost	$ 13,000	$ 1,500	$ 2,500	$ 2,500		$ 1,300
	Headend/Controller (per 50K sq.ft.)	$ 50,000	$ 130,000	$ 60,000			$ 5,000
	Base station (DAS only)	$ 30,000					
	Cabling ($ per ft)	$ 3	$ 1	$ 3	$ 3		$ 3
	Installation Labor (per radio unit)	$ 5,000	$ 200	$ 250	$ 300		$ 200
	Design Labor (per project)	$ 50,000	$ 40,000	$ 20,000	$ 20,000		$ 20,000
	Maintenance & support	15%	15%	15%	15%		15%
	Radio service management (per radio/yr)				$ 600		
Total Capex							
	Headend/Controller	$ 200,000	$ 520,000	$ 60,000			$ 20,000
	Radios (remote node/SC/AP units)	$ 1,300,000	$ 1,800,000	$ 1,500,000	$ 500,000		$ 520,000
	Networking			$ 180,000	$ 60,000		$ 100,000
	Base station	$ 30,000					
	Cabling & Misc	$ 360,000	$ 24,495	$ 51,962	$ 30,000		$ 42,426
	Installation Labor (per radio unit)	$ 500,000	$ 240,000	$ 150,000	$ 60,000		$ 80,000
	Design services Labor	$ 50,000	$ 40,000	$ 20,000	$ 20,000		$ 20,000
	TOTAL	**$ 2,390,000**	**$ 2,584,495**	**$ 1,941,962**	**$ 650,000**		**$ 762,426**
Total Opex per Year							
	Maintenance & support	$ 229,500	$ 348,000	$ 261,000	$ 84,000		$ 96,000
	Radio service management				$ 120,000		
	Power	$ 315,360	$ 37,843	$ 47,304	$ 15,768		$ 12,614
	Space (floor space for equipment)	$ 80,000	$ 8,000	$ 8,000	$ 8,000		$ 8,000
	Backhaul	$ 96,000	$ 96,000	$ 96,000	$ 96,000		$ 96,000
	TOTAL	**$ 720,860**	**$ 489,843**	**$ 412,304**	**$ 323,768**		**$ 212,614**
		DAS	**DRS/RRH**	**Lic. Small Cell**	**CBRS Small Cell**		**Carrier Wi-Fi**
8-year NPV (at 10% WACC)		**$6,018,462**	**$4,962,818**	**$3,965,031**	**$2,318,187**		**$1,827,397**
(NPV cost) $/sq.ft.		**$3.01**	**$2.48**	**$1.98**	**$1.16**		**$0.91**
Value of Wireless ($/sq.ft.)							
to	Enterprise	$ 3.10	$ 3.10	$ 3.10	$ 3.10	$ 3.10	$ 3.10
to	Mobile operator	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09	$ 0.09
Breakeven (months)							
for	Enterprise	1.0	0.8	0.6	0.4		0.3
for	Mobile operator	34.9	28.8	23.0	13.4		10.6

Airports and Subway Stations

Key assumptions about equipment and labor costs, traffic profile, and value of wireless to an operator and an enterprise (airport authority) are shown below:

		DAS	DRS/RRH	Lic. Small Cell	CBRS Small Cell	Repeater	Carrier Wi-Fi
Venue & Traffic Profile							
	Venue size (sq. ft.)	630,000	630,000	630,000	630,000	630,000	630,000
	Mobile operators supported	3	3	3	3		3
	User density (user/sq.ft.)	0.0025	0.0025	0.0025	0.0025		0.0025
	Coverage per radio node (sq.ft./radio)	80,000	10,000	10,000	10,000		5,000
	Total users (peak)	5,561	5,561	5,561	5,561		-
	Bandwidth (Mbps, peak)	658	658	658	658	658	658
	Total Radio units	**24**	**378**	**189**	**63**		**126**
	Cabling (ft)	1,929	7,716	5,456	3,150		4,455
Capex & Opex Costs							
	Radio unit cost	$ 13,000	$ 1,500	$ 2,500	$ 2,500		$ 1,300
	Headend/Controller (per 50K sq.ft.)	$ 50,000	$ 130,000	$ 60,000			$ 5,000
	Base station (DAS only)	$ 30,000					
	Cabling ($ per ft)	$ 3	$ 1	$ 3	$ 3		$ 3
	Installation Labor (per radio unit)	$ 5,000	$ 200	$ 250	$ 300		$ 200
	Design Labor (per project)	$ 30,000	$ 20,000	$ 10,000	$ 10,000		$ 10,000
	Maintenance & support	15%	15%	15%	15%		15%
	Radio service management (per radio/yr)				$ 600		
Total Capex							
	Headend/Controller	$ 63,000	$ 163,800	$ 18,900			$ 6,300
	Radios (remote node/SC/AP units)	$ 307,125	$ 567,000	$ 472,500	$ 157,500		$ 163,800
	Networking			$ 138,900	$ 46,300		$ 31,500
	Base station	$ 30,000					
	Cabling	$ 113,400	$ 7,716	$ 3,858	$ 3,858		$ 3,858
	Installation Labor (per radio unit)	$ 118,125	$ 75,600	$ 47,250	$ 18,900		$ 25,200
	Design services Labor	$ 30,000	$ 20,000	$ 10,000	$ 10,000		$ 10,000
	TOTAL	**$ 631,650**	**$ 814,116**	**$ 681,408**	**$ 226,558**		**$ 230,658**
Total Opex per Year							
	Maintenance & support	$ 60,019	$ 109,620	$ 94,545	$ 30,570		$ 30,240
	Radio service management				$ 37,800		
	Power	$ 74,504	$ 11,921	$ 14,901	$ 4,967		$ 3,974
	Space (floor space for equipment)	$ 80,000	$ 8,000	$ 8,000	$ 8,000		$ 8,000
	Backhaul	$ 18,000	$ 18,000	$ 18,000	$ 18,000		$ 18,000
	TOTAL	**$ 232,523**	**$ 147,541**	**$ 135,446**	**$ 99,337**		**$ 60,214**
		DAS	**DRS/RRH**	**Lic. Small Cell**	**CBRS Small Cell**		**Carrier Wi-Fi**
8-year NPV (at 10% WACC)		**$1,814,718**	**$1,527,224**	**$1,342,055**	**$735,917**		**$530,924**
(NPV cost) $/sq.ft.		**$2.88**	**$2.42**	**$2.13**	**$1.17**		**$0.84**
Value of Wireless ($/sq.ft.)							
to	Enterprise	$ 2.86	$ 2.86	$ 2.86	$ 2.86	$ 2.86	$ 2.86
to	Mobile operator	$ 0.12	$ 0.12	$ 0.12	$ 0.12	$ 0.12	$ 0.12
Breakeven (months)							
for	Enterprise	1.0	0.8	0.7	0.4	0.0	0.3
for	Mobile operator	24.5	20.6	18.1	9.9	0.0	7.2

Hotels

Key assumptions about equipment and labor costs, traffic profile, and value of wireless to an operator and a hotel enterprise are shown below:

		DAS	DRS/RRH	Lic. Small Cell	CBRS Small Cell	Repeater	Carrier Wi-Fi
Venue & Traffic Profile							
	Venue size (sq. ft.)	150,000	150,000	150,000	150,000	150,000	150,000
	Mobile operators supported	3	3	3	3	3	3
	User density (user/sq.ft.)	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
	Coverage per radio node (sq.ft./radio)	100,000	10,000	10,000	10,000	10,000	5,000
	Total users (peak)	750	750	750	750	750	750
	Bandwidth (Mbps, peak)	20	20	20	20	20	20
	Total Radio units	**6**	**90**	**45**	**15**	**15**	**30**
	Cabling (ft)	474	1,837	1,299	750	-	1,061
Capex & Opex Costs							
	Radio unit cost	$ 13,000	$ 1,500	$ 2,500	$ 2,500	$ 1,000	$ 1,000
	Headend/Controller (per 50K sq.ft.)	$ 50,000	$ 130,000	$ 60,000			$ 5,000
	Small Cell as a signal source (DAS only)	$ 1,500					
	Cabling ($ per ft)	$ 3	$ 1	$ 3	$ 3	$ 3	$ 3
	Installation Labor (per radio unit)	$ 5,000	$ 200	$ 250	$ 300	$ 250	$ 200
	Design Labor (per project)	$ 5,000	$ 4,000	$ 2,000	$ 2,000	$ 2,000	$ 2,000
	Maintenance & support	15%	15%	15%	15%	15%	15%
	Radio service management (per radio/yr)				$ 600		
Total Capex							
	Headend/Controller	$ 15,000	$ 39,000	$ 10,000			$ 5,000
	Radios (remote node/SC/AP units)	$ 78,000	$ 135,000	$ 112,500	$ 37,500	$ 15,000	$ 30,000
	Networking			$ 2,500	$ 2,500		$ 7,500
	Base station (small cell)	$ 2,500					
	Cabling	$ 27,000	$ 1,837	$ 919	$ 919	$ 919	$ 919
	Installation Labor (per radio unit)	$ 30,000	$ 18,000	$ 11,250	$ 4,500	$ 750	$ 6,000
	Design services Labor	$ 5,000	$ 4,000	$ 2,000	$ 2,000	$ 500	$ 2,000
	TOTAL	**$ 152,500**	**$ 193,837**	**$ 137,169**	**$ 45,419**	**$ 16,669**	**$ 49,419**
Total Opex per Year							
	Maintenance & support	$ 14,325	$ 26,100	$ 18,750	$ 6,000	$ 2,250	$ 6,375
	Radio service management				$ 9,000		
	Power	$ 473	$ 2,838	$ 3,548	$ 1,183	$ 1,183	$ 946
	Space (floor space for equipment)	$ 2,000	$ 2,000	$ 2,000	$ 2,000		$ 2,000
	Backhaul	$ 1,200	$ 1,200	$ 1,200	$ 1,200	$ 1,200	$ 1,200
	TOTAL	**$ 17,998**	**$ 32,138**	**$ 25,498**	**$ 19,383**	**$ 4,633**	**$ 10,521**
		DAS	**DRS/RRH**	**Lic. Small Cell**	**CBRS Small Cell**	**Repeater**	**Carrier Wi-Fi**
8-year NPV (at 10% WACC)		**$234,655**	**$347,671**	**$260,728**	**$144,694**	**$39,868**	**$101,055**
(NPV cost) $/sq.ft.		**$1.56**	**$2.32**	**$1.74**	**$0.96**	**$0.27**	**$0.67**
Value of Wireless ($/sq.ft.)							
to	Enterprise	$ 5.33	$ 5.33	$ 5.33	$ 5.33	$ 5.33	$ 5.33
to	Mobile operator	$ 0.01	$ 0.01	$ 0.01	$ 0.01	$ 0.01	$ 0.01
Breakeven (months)							
for	Enterprise	0.3	0.4	0.3	0.2	0.0	0.1
for	Mobile operator	133.7	198.1	148.6	82.4	22.7	57.6

Hospitals

Key assumptions about equipment and labor costs, traffic profile, and value of wireless to an operator and a hospital are shown below:

		DAS	DRS/RRH	Lic. Small Cell	CBRS Small Cell	Repeater	Carrier Wi-Fi
Venue & Traffic Profile							
	Venue size (sq. ft.)	300,000	300,000	300,000	300,000	300,000	300,000
	Mobile operators supported	3	3	3	3		3
	User density (user/sq.ft.)	0.0030	0.0030	0.0030	0.0030		0.0030
	Coverage per radio node (sq.ft./radio)	100,000	10,000	10,000	10,000		5,000
	Total users (peak)	1,800	1,800	1,800	1,800		-
	Bandwidth (Mbps, peak)	43	43	43	43	43	43
	Total Radio units	**9**	**180**	**90**	**30**		**60**
	Cabling (ft)	822	3,674	2,598	1,500		2,121
Capex & Opex Costs							
	Radio unit cost	$ 13,000	$ 1,500	$ 2,500	$ 2,500		$ 1,000
	Headend/Controller (per 50K sq.ft.)	$ 50,000	$ 130,000	$ 60,000			$ 5,000
	Small Cell as a signal source (DAS only)	$ 5,000					
	Cabling ($ per ft)	$ 3	$ 1	$ 3	$ 3		$ 3
	Installation Labor (per radio unit)	$ 5,000	$ 200	$ 250	$ 300		$ 200
	Design Labor (per project)	$ 20,000	$ 10,000	$ 5,000	$ 5,000		$ 5,000
	Maintenance & support	15%	15%	15%	15%		15%
	Radio service management (per radio/yr)				$ 600		
Total Capex							
	Headend/Controller	$ 30,000	$ 78,000	$ 9,000			$ 3,000
	Radios (remote node/SC/AP units)	$ 117,000	$ 270,000	$ 225,000	$ 75,000		$ 60,000
	Networking			$ 44,000	$ 43,000		$ 15,000
	Base station	$ 5,000					
	Cabling	$ 54,000	$ 3,674	$ 1,837	$ 1,837		$ 1,837
	Installation Labor (per radio unit)	$ 45,000	$ 36,000	$ 22,500	$ 9,000		$ 12,000
	Design services Labor	$ 20,000	$ 10,000	$ 5,000	$ 5,000		$ 5,000
	TOTAL	**$ 251,000**	**$ 387,674**	**$ 302,337**	**$ 128,837**		**$ 91,837**
Total Opex per Year							
	Maintenance & support	$ 22,800	$ 52,200	$ 41,700	$ 17,700		$ 11,700
	Radio service management				$ 18,000		
	Power	$ 28,382	$ 5,676	$ 7,096	$ 2,365		$ 1,892
	Space (floor space for equipment)	$ 20,000	$ 8,000	$ 8,000	$ 8,000		$ 8,000
	Backhaul	$ 1,800	$ 1,800	$ 1,800	$ 1,800		$ 1,800
	TOTAL	**$ 72,982**	**$ 67,676**	**$ 58,596**	**$ 47,865**		**$ 23,392**
		DAS	**DRS/RRH**	**Lic. Small Cell**	**CBRS Small Cell**		**Carrier Wi-Fi**
8-year NPV (at 10% WACC)		**$617,538**	**$713,480**	**$587,455**	**$372,482**		**$208,284**
(NPV cost) $/sq.ft.		**$2.06**	**$2.38**	**$1.96**	**$1.24**		**$0.69**
Value of Wireless ($/sq.ft.)							
to	Enterprise	$ 3.16	$ 3.16	$ 3.16	$ 3.16	$ 3.16	$ 3.16
to	Mobile operator	$ 0.02	$ 0.02	$ 0.02	$ 0.02	$ 0.02	$ 0.02
Breakeven (months)							
for	Enterprise	0.7	0.8	0.6	0.4	0.0	0.2
for	Mobile operator	127.1	146.8	120.9	76.6	0.0	42.9

Multi-Tenant Hi-Rise Buildings

Key assumptions about equipment and labor costs, traffic profile, and value of wireless to an operator and a multi-tenant office building owner are shown below:

		DAS	DRS/RRH	Lic. Small Cell	CBRS Small Cell	Repeater	Carrier Wi-Fi
Venue & Traffic Profile							
	Venue size (sq. ft.)	500,000	500,000	500,000	500,000	500,000	500,000
	Mobile operators supported	3	3	3	3		3
	User density (user/sq.ft.)	0.0067	0.0067	0.0067	0.0067		0.0067
	Coverage per radio node (sq.ft./radio)	100,000	10,000	10,000	10,000		5,000
	Total users (peak)	3,333	3,333	3,333	3,333	3,333	3,333
	Bandwidth (Mbps, peak)	74	74	74	74	74	74
	Total Radio units	**15**	**300**	**150**	**50**		**100**
	Cabling (ft)	1,369	6,124	4,330	2,500		3,536
Capex & Opex Costs							
	Radio unit cost	$ 13,000	$ 1,500	$ 2,500	$ 2,500		$ 1,000
	Headend/Controller (per 50K sq.ft.)	$ 50,000	$ 130,000	$ 60,000			$ 5,000
	Base station (DAS only)	$ 30,000					
	Cabling ($ per ft)	$ 3	$ 1	$ 3	$ 3		$ 3
	Installation Labor (per radio unit)	$ 5,000	$ 200	$ 250	$ 300		$ 200
	Design Labor (per project)	$ 30,000	$ 20,000	$ 10,000	$ 10,000		$ 10,000
	Maintenance & support	15%	15%	15%	15%		15%
	Radio service management (per radio/yr)				$ 600		
Total Capex							
	Headend/Controller	$ 50,000	$ 130,000	$ 15,000			$ 5,000
	Radios (remote node/SC/AP units)	$ 195,000	$ 450,000	$ 375,000	$ 125,000		$ 100,000
	Networking			$ 75,000	$ 25,000		$ 25,000
	Base station	$ 30,000					
	Cabling	$ 90,000	$ 6,124	$ 3,062	$ 3,062		$ 3,062
	Installation Labor (per radio unit)	$ 75,000	$ 60,000	$ 37,500	$ 15,000		$ 20,000
	Design services Labor	$ 30,000	$ 20,000	$ 10,000	$ 10,000		$ 10,000
	TOTAL	**$ 440,000**	**$ 646,124**	**$ 505,562**	**$ 168,062**		**$ 153,062**
Total Opex per Year							
	Maintenance & support	$ 41,250	$ 87,000	$ 69,750	$ 22,500		$ 19,500
	Radio service management				$ 30,000		
	Power	$ 47,304	$ 9,461	$ 11,826	$ 3,942		$ 3,154
	Space (floor space for equipment)	$ 80,000	$ 8,000	$ 8,000	$ 8,000		$ 8,000
	Backhaul	$ 1,800	$ 1,800	$ 1,800	$ 1,800	$ 1,800	$ 1,800
	TOTAL	**$ 170,354**	**$ 106,261**	**$ 91,376**	**$ 66,242**		**$ 32,454**
		DAS	**DRS/RRH**	**Lic. Small Cell**	**CBRS Small Cell**		**Carrier Wi-Fi**
8-year NPV (at 10% WACC)		**$1,308,826**	**$1,154,279**	**$947,086**	**$506,180**		**$312,285**
(NPV cost) $/sq.ft.		**$2.62**	**$2.31**	**$1.89**	**$1.01**		**$0.62**
Value of Wireless ($/sq.ft.)							
to	Enterprise	$ 2.07	$ 2.07	$ 2.07	$ 2.07	$ 2.07	$ 2.07
to	Mobile operator	$ 0.03	$ 0.03	$ 0.03	$ 0.03	$ 0.03	$ 0.03
Breakeven (months)							
for	Enterprise	1.3	1.1	0.9	0.5	0.0	0.3
for	Mobile operator	98.2	86.6	71.0	38.0	0.0	23.4

Retail Shopping Malls

Key assumptions about equipment and labor costs, traffic profile, and value of wireless to an operator and a retail mall enterprise are shown below:

		DAS	DRS/RRH	Lic. Small Cell	CBRS Small Cell	Repeater	Carrier Wi-Fi
Venue & Traffic Profile							
	Venue size (sq. ft.)	900,000	900,000	900,000	900,000	900,000	900,000
	Mobile operators supported	3	3	3	3		3
	User density (user/sq.ft.)	0.0019	0.0019	0.0019	0.0019		0.0019
	Coverage per radio node (sq.ft./radio)	100,000	10,000	10,000	10,000		5,000
	Total users (peak)	2,237	2,237	2,237	2,237	2,237	2,237
	Bandwidth (Mbps, peak)	99	99	99	99	99	99
	Total Radio units	**27**	**540**	**270**	**90**		**180**
	Cabling (ft)	2,465	11,023	7,794	4,500		6,364
Capex & Opex Costs							
	Radio unit cost	$ 13,000	$ 1,500	$ 2,500	$ 2,500		$ 1,000
	Headend/Controller (per 50K sq.ft.)	$ 50,000	$ 130,000	$ 60,000			$ 5,000
	Base station (DAS only)	$ 30,000					
	Cabling ($ per ft)	$ 3	$ 1	$ 3	$ 3		$ 3
	Installation Labor (per radio unit)	$ 5,000	$ 200	$ 250	$ 300		$ 200
	Design Labor (per project)	$ 50,000	$ 40,000	$ 20,000	$ 20,000		$ 20,000
	Maintenance & support	15%	15%	15%	15%		15%
	Radio service management (per radio/yr)				$ 600		
Total Capex							
	Headend/Controller	$ 90,000	$ 234,000	$ 27,000			$ 9,000
	Radios (remote node/SC/AP units)	$ 351,000	$ 810,000	$ 675,000	$ 225,000		$ 180,000
	Networking			$ 147,000	$ 49,000		$ 45,000
	Base station	$ 30,000					
	Cabling	$ 162,000	$ 11,023	$ 5,511	$ 5,511		$ 5,511
	Installation Labor (per radio unit)	$ 135,000	$ 108,000	$ 67,500	$ 27,000		$ 36,000
	Design services Labor	$ 50,000	$ 40,000	$ 20,000	$ 20,000		$ 20,000
	TOTAL	**$ 768,000**	**$ 1,163,023**	**$ 922,011**	**$ 306,511**		**$ 275,511**
Total Opex per Year							
	Maintenance & support	$ 70,650	$ 156,600	$ 127,350	$ 41,100		$ 35,100
	Radio service management				$ 54,000		
	Power	$ 85,147	$ 17,029	$ 21,287	$ 7,096		$ 5,676
	Space (floor space for equipment)	$ 80,000	$ 8,000	$ 8,000	$ 8,000		$ 8,000
	Backhaul	$ 3,600	$ 3,600	$ 3,600	$ 3,600	$ 3,600	$ 3,600
	TOTAL	**$ 239,397**	**$ 185,229**	**$ 160,237**	**$ 113,796**		**$ 52,376**
		DAS	**DRS/RRH**	**Lic. Small Cell**	**CBRS Small Cell**		**Carrier Wi-Fi**
8-year NPV (at 10% WACC)		**$1,975,348**	**$2,045,479**	**$1,693,044**	**$885,738**		**$529,890**
(NPV cost) $/sq.ft.		**$2.19**	**$2.27**	**$1.88**	**$0.98**		**$0.59**
Value of Wireless ($/sq.ft.)							
to	Enterprise	$ 1.58	$ 1.58	$ 1.58	$ 1.58	$ 1.58	$ 1.58
to	Mobile operator	$ 0.14	$ 0.14	$ 0.14	$ 0.14	$ 0.14	$ 0.14
Breakeven (months)							
for	Enterprise	1.4	1.4	1.2	0.6	0.0	0.4
for	Mobile operator	16.2	16.8	13.9	7.3	0.0	4.3

Corporate Office / Campus

Key assumptions about equipment and labor costs, traffic profile, and value of wireless to an operator and a corporate headquarter or campus are shown below:

		DAS	DRS/RRH	Lic. Small Cell	CBRS Small Cell Repeater		Carrier Wi-Fi
Venue & Traffic Profile							
	Venue size (sq. ft.)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Mobile operators supported	3	3	3	3		3
	User density (user/sq.ft.)	0.0067	0.0067	0.0067	0.0067		0.0067
	Coverage per radio node (sq.ft./radio)	100,000	10,000	10,000	10,000		5,000
	Total users (peak)	13,333	13,333	13,333	13,333	13,333	13,333
	Bandwidth (Mbps, peak)	148	148	148	148	148	148
	Total Radio units	**30**	**600**	**300**	**100**		**200**
	Cabling (ft)	2,739	12,247	8,660	5,000		7,071
Capex & Opex Costs							
	Radio unit cost	$ 13,000	$ 1,500	$ 2,500	$ 2,500		$ 1,000
	Headend/Controller (per 50K sq.ft.)	$ 50,000	$ 130,000	$ 60,000			$ 5,000
	Base station (DAS only)	$ 30,000					
	Cabling ($ per ft)	$ 3	$ 1	$ 3	$ 3		$ 3
	Installation Labor (per radio unit)	$ 5,000	$ 200	$ 250	$ 300		$ 200
	Design Labor (per project)	$ 50,000	$ 40,000	$ 20,000	$ 20,000		$ 20,000
	Maintenance & support	15%	15%	15%	15%		15%
	Radio service management (per radio/yr)				$ 600		
Total Capex							
	Headend/Controller	$ 100,000	$ 260,000	$ 30,000			$ 10,000
	Radios (remote node/SC/AP units)	$ 390,000	$ 900,000	$ 750,000	$ 250,000		$ 200,000
	Networking			$ 150,000	$ 50,000		$ 50,000
	Base station	$ 30,000					
	Cabling	$ 180,000	$ 12,247	$ 6,124	$ 6,124		$ 6,124
	Installation Labor (per radio unit)	$ 150,000	$ 120,000	$ 75,000	$ 30,000		$ 40,000
	Design services Labor	$ 50,000	$ 40,000	$ 20,000	$ 20,000		$ 20,000
	TOTAL	**$ 850,000**	**$ 1,292,247**	**$ 1,011,124**	**$ 336,124**		**$ 306,124**
Total Opex per Year							
	Maintenance & support	$ 78,000	$ 174,000	$ 139,500	$ 45,000		$ 39,000
	Radio service management				$ 60,000		
	Power	$ 94,608	$ 18,922	$ 23,652	$ 7,884		$ 6,307
	Space (floor space for equipment)	$ 80,000	$ 8,000	$ 8,000	$ 8,000		$ 8,000
	Backhaul	$ 3,600	$ 3,600	$ 3,600	$ 3,600	$ 3,600	$ 3,600
	TOTAL	**$ 256,208**	**$ 204,522**	**$ 174,752**	**$ 124,484**		**$ 56,907**
		DAS	**DRS/RRH**	**Lic. Small Cell**	**CBRS Small Cell Repeater**		**Carrier Wi-Fi**
8-year NPV (at 10% WACC)		**$2,139,578**	**$2,265,878**	**$1,851,492**	**$969,680**	**$0**	**$581,890**
(NPV cost) $/sq.ft.		**$2.14**	**$2.27**	**$1.85**	**$0.97**	**$0.00**	**$0.58**
Value of Wireless ($/sq.ft.)							
to	Enterprise	$ 33.33	$ 33.33	$ 33.33	$ 33.33	$ 33.33	$ 33.33
to	Mobile operator	$ 0.03	$ 0.03	$ 0.03	$ 0.03	$ 0.03	$ 0.03
Breakeven (months)							
for	Enterprise	0.06	0.07	0.06	0.03	0.00	0.02
for	Mobile operator	80.23	84.97	69.43	36.36	0.00	21.82

Light Industrial Buildings

Key assumptions about equipment and labor costs, traffic profile, and value of wireless to an operator and a light industrial enterprise are shown below:

	DAS	DRS/RRH	Lic. Small Cell	CBRS Small Cell	Repeater	Carrier Wi-Fi
Venue & Traffic Profile						
Venue size (sq. ft.)	200,000	200,000	200,000	200,000	200,000	200,000
Mobile operators supported	3	3	3	3	3	3
User density (user/sq.ft.)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Coverage per radio node (sq.ft./radio)	100,000	10,000	10,000	10,000	10,000	5,000
Total users (peak)	0.1	0.1	0.1	0.1	0.1	0.1
Bandwidth (Mbps, peak)	0.004	0.004	0.004	0.004	0.004	0.004
Total Radio units	**6**	**120**	**60**	**20**	**20**	**40**
Cabling (ft)	548	2,449	1,732	1,000	-	1,414
Capex & Opex Costs						
Radio unit cost	$ 13,000	$ 1,500	$ 2,500	$ 2,500	$ 1,000	$ 1,000
Headend/Controller (per 50K sq.ft.)	$ 50,000	$ 130,000	$ 60,000			$ 5,000
Signal Source (repeater)	$ 1,000					
Cabling ($ per ft)	$ 3	$ 1	$ 3	$ 3	$ -	$ 3
Installation Labor (per radio unit)	$ 5,000	$ 200	$ 250	$ 300	$ 250	$ 200
Design Labor (per project)	$ 5,000	$ 4,000	$ 2,000	$ 2,000	$ 2,000	$ 20,000
Maintenance & support	15%	15%	15%	15%	15%	15%
Radio service management (per radio/yr)				$ 600		
Total Capex						
Headend/Controller	$ 20,000	$ 52,000	$ 10,000			$ 2,000
Radios (remote node/SC/AP units)	$ 78,000	$ 180,000	$ 150,000	$ 50,000	$ 20,000	$ 40,000
Networking			$ 2,500	$ 2,500		$ 10,000
Base station (small cell)	$ 2,500					
Cabling	$ 36,000	$ 2,449	$ 1,225	$ 1,225	$ 1,225	$ 1,225
Installation Labor (per radio unit)	$ 30,000	$ 24,000	$ 15,000	$ 6,000	$ 1,000	$ 8,000
Design services Labor	$ 5,000	$ 4,000	$ 2,000	$ 2,000	$ 500	$ 20,000
TOTAL	**$ 166,500**	**$ 258,449**	**$ 178,725**	**$ 59,725**	**$ 22,225**	**$ 61,225**
Total Opex per Year						
Maintenance & support	$ 15,075	$ 34,800	$ 24,375	$ 7,875	$ 3,000	$ 7,800
Radio service management				$ 12,000		
Power	$ 473	$ 3,784	$ 1,892	$ 631	$ 1,577	$ 1,261
Space (floor space for equipment)	$ 8,000	$ 8,000	$ 8,000	$ 8,000		$ 8,000
Backhaul (no additional link required due	$ -	$ -	$ -	$ -	$ -	$ -
TOTAL	**$ 23,548**	**$ 46,584**	**$ 34,267**	**$ 28,506**	**$ 4,577**	**$ 17,061**
	DAS	**DRS/RRH**	**Lic. Small Cell**	**CBRS Small Cell**	**Repeater**	**Carrier Wi-Fi**
8-year NPV (at 10% WACC)	**$276,991**	**$483,478**	**$345,290**	**$206,371**	**$44,621**	**$146,680**
(NPV cost) $/sq.ft.	**$1.38**	**$2.42**	**$1.73**	**$1.03**	**$0.22**	**$0.73**
Value of Wireless ($/sq.ft.)						
to Enterprise	$ 5.95	$ 5.95	$ 5.95	$ 5.95	$ 5.95	$ 5.95
to Mobile operator	$ 0.000002	$ 0.000002	$ 0.000002	$ 0.000002	$ 0.000002	$ 0.000002
Breakeven (months)						
for Enterprise	0.2	0.4	0.3	0.2	0.0	0.1
for Mobile operator	582,892.9	1,017,420.0	726,620.0	434,282.7	93,899.8	308,670.8

5 CBRS Impact – Which Verticals and How Much?

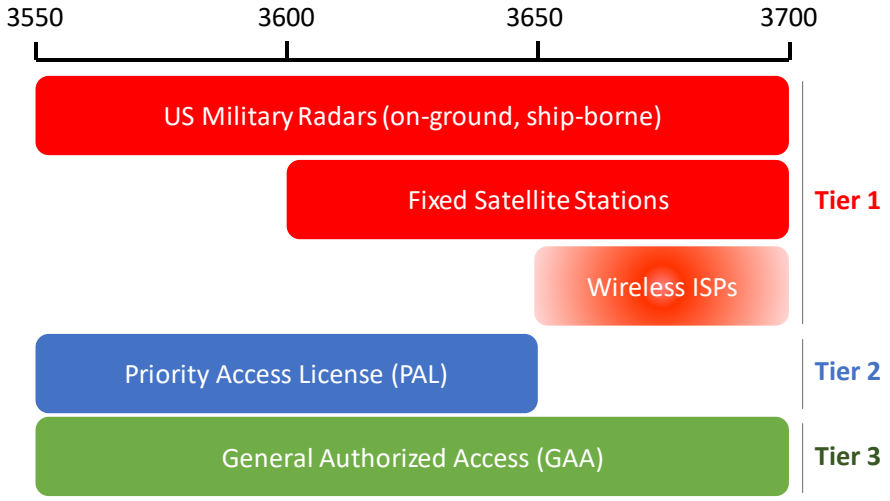
In last year's report, Mobile Experts had forecasted uncertain market impact of the 3.5GHz CBRS on the enterprise mobile infrastructure market. That view was largely based on lukewarm reception of the major operators in the United States. Since publication of that report, we have observed some big progress. All four major operators including Verizon, AT&T, T-Mobile US, and Sprint have since joined the CBRS Alliance, indicating an implicit interest in the CBRS spectrum. Moreover, Mobile Experts expects at least one of the tier 1 handset vendors will release a device that supports CBRS within the next year. While obstacles to sustainable business opportunities around CBRS remain, our view of the CBRS ecosystem and the viability of CBRS impact on the Enterprise Mobile Infrastructure marketplace has certainly brightened over the past six months.

Assuming that necessary handset and operator support for CBRS band is in place, key questions are:

1. How will CBRS capable small cells impact the Enterprise Mobile Infrastructure market?
2. Which vertical industries will be ripe for CBRS small cells adoption?

CBRS Primer and Key Advantages for In-Building Wireless

To make more spectrum available for wireless broadband use, the US Government (FCC) adopted dynamic spectrum sharing of the 3550-3700 MHz ("3.5GHz") band for commercial use. Formally known as Citizen Broadband Radio Service (CBRS), the 3.5GHz shared spectrum use is authorized into three tiers.



Source: Mobile Experts

Figure 16. CBRS Tiered Shared Spectrum Licensing

The tier 1 "incumbents," including ship-borne Navy radars, fixed satellite stations, and wireless ISPs, are protected from lower tier users at all times.[2] CBRS rules govern commercial tier 2 Priority Access License (PAL) and tier 3 General Authorized Access (GAA) users. Under the plan, up to 150MHz of spectrum are made available for commercial use on a shared basis with incumbent users, primarily military radars and fixed satellite stations. Each PAL license covers a 10MHz channel per census tract for a three-year term, and up to seven PALs can be assigned in a census tract. GAA users are permitted to use any portion of the 3.5GHz band not assigned to higher tier users. Until a competitive PAL auction takes place, up to 150MHz of the band is open for GAA "unlicensed" use dependent on tier 1 incumbent use.

The key dynamic spectrum channel assignment is handled by a Spectrum Access System (SAS) which maintains a database of all CBRS base stations, formally referred to as Citizen Band Service Devices (CBSDs). It works with environmental sensors known as Environmental Sensing Capability (ESC), mostly along coastal regions, to detect Navy radar activity. When radar use is detected, the ESC alerts the SAS, which then directs CBSDs to "move" over to other open channels. SAS enforces the three-tier licensing structure and dynamic channel assignments via centralized coordination.

LTE-based solutions in the CBRS band afford special advantages for in-building wireless market, including:

- Inexpensive "clean" spectrum in the favorable 3.5GHz mid-band;
- Robust ecosystem of handset and operator support; and
- Lower unit cost than other multi-operator mobile coverage solutions

The 150MHz of nearly idle spectrum in the CBRS band offers a tremendous new spectrum resource that can be allocated for indoor mobile networks.3 For mobile operators, dedicating the CBRS spectrum band for indoor networks frees up valuable licensed spectrum which would otherwise have to be allocated for the indoor use. More importantly, dedicating separate "neutral" spectrum for indoor networks eliminates possible co-channel interferences between macro and indoor networks. This in turn simplifies RF engineering and enables third-party neutral host providers or large enterprises to build out indoor LTE networks without close coordination with mobile operators. The novel tiered approach of shared spectrum also encourages success-based investment by a variety of stakeholders, not just the traditional mobile operators. With GAA open access, no spectrum ownership is required. This in turn enables enterprise-led indoor LTE network deployments without close coordination with mobile operators which has been a key impediment in wide spread adoption of DAS deployments--especially in mid-sized enterprises and venues.

[2] Wireless ISPs currently operating in the 3650-3700 MHz spectrum band will be required to operate under the Tier 2 or 3 access after an initial five-year 'grace' period.

[3] A major US mobile operator, on average, holds about 130MHz of licensed spectrum.

With all four tier 1 operators voicing support of CBRS, CBRS LTE small cells have become a realistic multi-operator mobile coverage solution. This is a major step because this kind of product fills the void in the marketplace between Wi-Fi and DAS. While Wi-Fi is considered inexpensive, it lacks in seamless mobile voice services. On the other hand, the multi-operator DAS solution is considered too expensive for many enterprises, not to mention the difficulty of securing a signal source from the operators. CBRS small cells with inherent multi-operator support and simplicity of Wi-Fi like installation can provide a cost-effective mobile coverage solution for third-party neutral host providers and large enterprises alike. Mobile operators' self-interest to leverage the CBRS band for their own capacity expansion is likely to hasten the enterprise adoption of CBRS as enterprises see broad availability of CBRS-capable handsets coming to marketplace.

Enterprise Mobile Infrastructure Decision Criteria

Cost is an important consideration for many enterprises, but it is not the only factor in determination of which in-building wireless solution to deploy. For enterprises simply requiring wireless data connectivity to the Internet for browsing and streaming, Wi-Fi may be perfectly fine. For most enterprises and vertical industries, the in-building wireless solution must not simply provide wireless connectivity but also, seamless voice and data services that their visitors and workers expect from their mobile devices indoors and out.

While there will be specific requirements that may drive an enterprise to adopt one solution versus another, Mobile Experts believes that enterprises will generally draw upon following criteria for determining which in-building mobile infrastructure would be right for them:

1. Cost: The total cost of ownership, including capex and on-going opex components will be major consideration for most enterprises across vertical industries. Besides major stadium venue owners and sports franchise owners who may be willing to invest in venue facilities to enhance fan experience to draw consumers to come to live games and events, most enterprises especially those in low-margin businesses will be very price-sensitive. Major DAS projects ranging in millions of dollars will be too expensive for smaller venue owners like midsize hotel owners. For these price-sensitive markets, CBRS small cells that can provide multi-operator support and provide seamless cellular services have a big appeal.

2. Coverage vs. Capacity: For most enterprises, multi-operator mobile coverage is a key reason for in-building mobile infrastructure investment. For venues with extreme traffic density such as sporting venues where fans regularly share live experiences with their social networks, mobile coverage is table stakes, and capacity increase drives mobile infrastructure investments. In most cases, these venues deploy multiple technologies to get ahead of 'data tsunami' – deploying high-density of Wi-Fi access points along with multiple carriers and sectors over increasing number of DAS radio nodes. In most public venues like hotels, hospitals, the multi-operator mobile

coverage is a fundamental requirement for having a good mobile service to its customers. One exception may be in a corporate headquarters environment where a specific operator may deploy operator-specific small cells and/or DAS to enable robust coverage and capacity for key corporate customer to retain or win over a big corporate account.

3. Control for Value-Added Enterprise Applications: Although not directly related to in-building mobile infrastructure systems, some enterprises are looking for control points or product features such that value-added enterprise applications can be enabled on top of wireless networks. For example, some industrial warehouse venues are leveraging Wi-Fi networks along with Bluetooth capability to enable location services to target enterprise-specific application that improves customer experience or increase worker productivity. Similarly, Huawei's LampSite is sometimes positioned as an enterprise application platform that enables location and advertising services for the enterprise venue owner, so that enterprises are incentivized to fund the projects directly.

4. Ecosystem Support (for Installation and Maintenance): Having trusted systems integrators who can take on complex RF installation projects on behalf of enterprises may simply be the key winning criteria. Some markets lack a mature ecosystem of local and regional infrastructure suppliers who can work with operators. In the United States, system integrators supporting DAS projects are many as those are higher value projects as compared to Wi-Fi deployments. One of the key challenges for enterprises is finding system integrators that are knowledgeable in Small Cell products and integrating them with mobile operator core networks and processes.

5. Wireless Link Quality: Enterprise expectation of wireless quality of service indoor can impact what solution to choose based on other decision criteria. If enterprise does not require reliable and consistent wireless connectivity, Wi-Fi may be sufficient. On the other hand, some enterprises like hospitals may require mission-critical applications running over wireless networks and need reliable and consistent network services that may require LTE network use over Wi-Fi.

	Cost	Coverage vs. Capacity	Control and Enterprise Apps	Ecosystem support	Wireless Link Quality
Stadiums	Price indifferent	High capacity demand	Control for value-added venue applications	Extensive system integrators exist already	High QoS expected
Airports / Subways	Mostly price indifferent	High capacity demand	Control for venue services desired	System integrators exist already	Consumer-grade is good enough
Hotels	Price-sensitive (low cost)	Coverage as 1st priority; capacity req'd in select areas (conf. halls)		Ease of installation (like Wi-Fi) demanded	Consumer-grade is good enough
Hospitals	Somewhat price-sensitive	Multi-operator coverage in public areas		Ease of installation (like Wi-Fi) demanded	Reliable link required for mission critical apps
Retail Malls	Price-sensitive (low cost)	Multi-operator coverage is a key priority	Control for value-added venue services	Ease of installation (like Wi-Fi) demanded	
Multi-tenant Hi-Rise Buildings	Mostly price indifferent	Multi-operator coverage is a key priority		Ease of installation (like Wi-Fi) demanded	
Corp. HQ / Campus	Mostly price indifferent	Coverage as 1st priority; capacity expected	Control for enterprise-specific applications		Seamless access and quality
Light Industrial	Price-sensitive (low cost)	Coverage first		Ease of installation (like Wi-Fi) demanded	

Source: Mobile Experts

Figure 17. Enterprise Mobile Infrastructure Decision Criteria by Vertical Industry

Enterprise Mobile Infrastructure Product Fit

Based on the decision criteria laid out previously, DAS offers flexible features that can meet most of the key requirements of most of the key vertical segments. It offers flexible multi-operator support that can handle multiple frequency bands and air interface technologies and provide seamless in-building network control and capacity handling through separate base station for signal source. However, it comes with a hefty total cost of ownership in millions of dollars that is too high for many enterprises in most of the vertical sectors besides large stadiums and key public transport venues. While traditional licensed small cells offer scalable approach to enhancing coverage and capacity indoors, most only support single operator, making them not a perfect fit for public venues like hotels and hospitals. Meanwhile, repeaters may be suitable for lightly trafficked venues like warehouses and enterprises in rural areas, but they are likely unsuitable for many enterprises in urban settings due to strain on macro base station user capacity handling. Finally, Carrier Wi-Fi offer cost-effective wireless data offload solution for most enterprises. However, its efficacy as a total mobile voice and data solution indoors has been marred by congestion conditions which deteriorate wireless link quality.

	Cost	Coverage vs. Capacity	Control and Enterprise Apps	Ecosystem support	Wireless Link Quality
DAS	$$$$ - expensive	Multi-operator coverage & high capacity		Extensive ecosystem in the USA	Engineered to be reliable
Licensed Small Cells (RRH/DRS)	$$$ - less (but single operator)	Single-operator coverage & scalable capacity		Smaller ecosystem than DAS	Engineered to be reliable
CBRS Small Cells	$$$ - less (and multi-operator)	Multi-operator coverage & scalable capacity	Possible	New, possibly in 2018	Theoretically robust and reliable
Repeaters	$ - cheap	Coverage only	Not applicable	Carrier-sanctioned repeaters available in the USA	Reliable
Carrier Wi-Fi	$$ - Inexpensive	Wireless data capacity	Available as add-on	Extensive ecosystem worldwide	Reliability not certain in congested areas

Source: Mobile Experts

Figure 18. Enterprise Mobile Infrastructure Products vs. Vertical Industry Decision Criteria

Which Vertical Segment Is Ripe for CBRS?

Based on decision criteria of industry verticals and best possible product fit against those criteria, we can surmise a rough product fit against different industry verticals. For example, we can conclude that highly engineered in-building solutions like DAS are best suited for large public venues like stadiums and airports with high density of users handling multitude of diverse operators, technologies, and frequency bands. The technology-agnostic nature of DAS makes it ideally suited for venue owners or neutral host providers to enable shared infrastructure model to multiple operators and stakeholders involved. On the other extreme, deploying highly engineered DAS would be "overkill" for smaller venues with limited traffic going over the network.

As shown in the figure below, DAS would be ideal for very high-traffic venues like stadiums and airports and other large mega venues in hospitality (large hotels with adjacent convention centers in Las Vegas for example) and hi-rise office buildings in urban corridors with metallic glass which limits "outside in" RF propagation indoors. Small Cells including DRS/RRH systems, which contain signal source embedded in baseband processing units, are well suited for smaller venues (say less than 500K sq. ft.) to provide scalable capacity where needed. For example, hospitals that require high-density capacity in select areas such as a lobby and emergency room area would be well served with Small Cells without having to retrofit the entire in-building facility. While today's licensed small cells can typically support single operator, CBRS can theoretically support multiple operators (assuming that those operators will support and carry CBRS-capable handsets in their inventory). This multi-operator aspect of CBRS Small Cell makes it a cost-effective alternative for smaller enterprises that are looking for Wi-Fi-like small cells that can support seamless LTE voice and data services in and out of buildings.

	DAS	Small Cells (DRS/RRH)	CBRS Small Cell	Repeater	Carrier Wi-Fi
Stadiums					data offload
Airports / Subways					data offload
Hotels				small hotels	data offload
Hospitals				rural	data offload
Retail Malls					data offload
Multi-tenant Hi-Rise Buildings					data offload
Corp. HQ / Campus		single operator			data offload
Light Industrial					data offload

Source: Mobile Experts

Note: Color coding indicates product 'fit' against decision criteria of each vertical industry… (GREEN – best fit; YELLOW – possible fit; RED – bad match; LIGHT GREEN – Wi-Fi can provide data offload but cannot provide seamless voice service)

Figure 19. DAS / Small Cell / CBRS / Repeater Product Fit vs. Vertical Industry

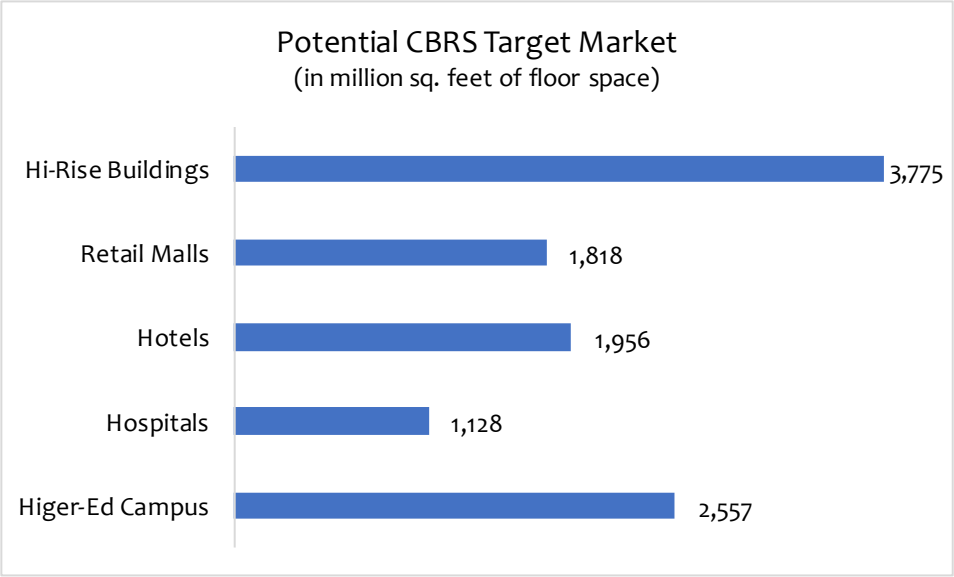
Repeaters are best suited for small venues, typically less than 50K square feet, to extend outside RF signal indoors to provide mobile coverage solution indoors. The actual capacity handling is carried out by nearby macro station. For this reason, this is not a preferred solution for most urban settings where operators are battling 'capacity crunch' situation with operators reporting 40-50% year-over-year growth in traffic use.

Finally, while Wi-Fi provides cost-effective means to provide wireless coverage and capacity solution across all vertical segments, it is still not reliable and robust enough to provide seamless mobile voice service especially in congested urban settings where it is typical to find tens of Wi-Fi SSID signals in a given location contending for a shared unlicensed spectrum. For some vertical segments, such as hospitals, unmanaged Wi-Fi networks are deemed unreliable and insecure for sensitive enterprise applications. Leveraging the LTE security framework and seamless authentication capability are viewed by some enterprises as key differentiator for moving sensitive enterprise applications onto mobile devices.

While CBRS small cells will likely be more expensive than Wi-Fi, the scalable deployment model makes it a flexible platform for many verticals including hotels, multi-tenant commercial buildings, corporate campuses, and retail malls to build their in-building networks over time, without a heavy up-front investment in day one.

How Much of In-Building Market Could CBRS Address?

Taking the match profile of CBRS Small Cells addressing the hotels, hospitals, retail malls, commercial office buildings, and higher-education vertical segments, and further segmenting out those venues that are between 50K – 500K square feet, we surmise that the CBRS small cells can address over **11B square feet** of commercial floor space across **56,000 buildings** in the United States across the different vertical segments as outlined below.



Source: US EIA, Mobile Experts

Chart 3: U.S. In-Building Commercial Space Addressable by CBRS Small Cells

The Commercial Office space, especially high-rise buildings represent the biggest vertical segment opportunity. Other notable vertical segments include hotels, hospitals, higher-education campuses, and retail malls. It should be noted that there are many more buildings that are below 50K square feet in size; however, we have excluded them for our target addressable market since they can be more cheaply addressed via repeaters. Likewise, we have excluded larger venues, i.e., those larger than 500K square feet in size, since they are likely better targeted by lower-cost "light DAS" products.

6 REGIONAL OUTLOOK

As noted in last year's report, cultural, economic, ecosystem maturity, and regulatory (spectrum policy) regime across different regions and countries impacts the development of business models and mobile infrastructure investment in enterprises. Enterprises in China and India behave very differently than western corporations in the USA and Europe. There are meaningful differences among enterprises in different regions as to who is responsible for indoor mobile services and who pays for enterprise mobile infrastructure equipment and on-going maintenance and service.

Here are some examples of factors that influence business model development and likely choice of solution for enterprise mobile infrastructure:

1. Economic/Political System: Enterprises based in capitalist countries will invest more readily in wireless equipment. Enterprises in communist countries, or any country with a top-down political structure, will generally rely on the mobile operators to take care of in-building coverage. In other words, enterprises that feel free to invest in telecom hardware will do so.

2. Ecosystem Maturity: North America and the UK have generally mature ecosystems of system integrators and neutral host providers for DAS and Wi-Fi installations. Hundreds of small, local companies support IT/telecom projects for companies and large DAS and Small Cell infrastructure projects for operators. Therefore, in the United States and the UK, we see quick development of an enterprise mobile infrastructure market. Other countries in Latin America, Eastern Europe, India, and Asia do not have rich ecosystems of system integrators and infrastructure companies at local levels to address specific enterprise needs across geographies and vertical industries.

3. Regulatory Regime: Many Western countries have deregulated the telecom market to separate wireline and wireless business groups. This means that in some countries, the mobile operator does not have access to many fiber assets. For example, we see a mix of wireless-only, wireline-only, and some fixed/mobile operators in the USA and Europe. Mobile operators in the USA look to wireline service providers for fiber backhaul. In contrast, many mobile operators in China, Japan and Korea also have significant fiber assets. With fixed line assets at their disposal, with low internal transfer pricing, these operators have been early proponents of CRAN architecture using Remote Radio Head designs which use high-bandwidth CPRI interfaces.

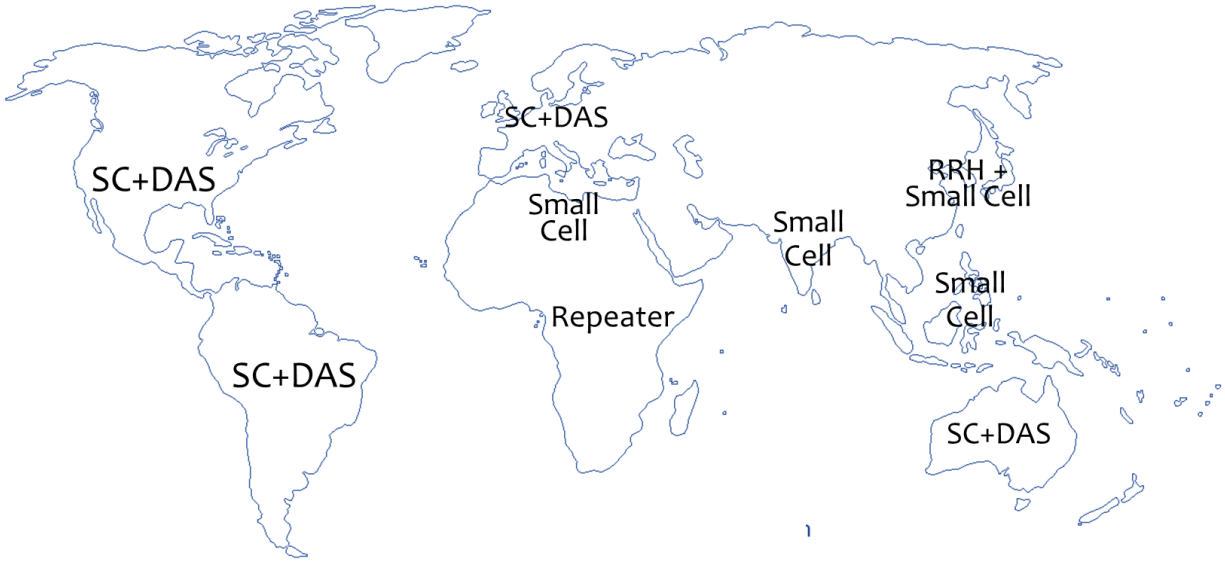
4. Spectrum: Countries that have released huge blocks of spectrum are generally more focused on deployment of macro base stations with spectrum overlay to more efficiently deploy capacity. However, for operators that are more spectrum-

constrained will need to source in-building solutions to more aggressively to expand mobile coverage, and to increase data capacity indoors to address the rising mobile traffic growth. This is necessary not only to meet the demand locally, but also to relieve strain on macro networks which is more critical in consumer perception of mobile service quality.

5. Industry Structure and Competition: Countries that have multiple strong mobile operators (i.e., with substantial share of subscribers) tend to move toward DAS solutions in key in-building mobile infrastructure projects such as stadiums and airports. To meet this growing need The USA and UK have highly developed DAS ecosystems because of the relatively even market share of multiple players in these countries. In Mexico, as a counter-example, Telcel dominates with 70% of the subscribers, so DAS project decisions are dependent upon the support of Telcel to be viable.

6. Competition and Profitability: The Average Revenue Per User is a key metric. Operators with high ARPU will naturally invest more in an in-building project to ensure that customers can keep generating revenue inside the building. Operators with low ARPU simply will not invest. Some operators are starting to use a metric such as "ARPU per square foot" to understand the potential ROI for investing in a building.

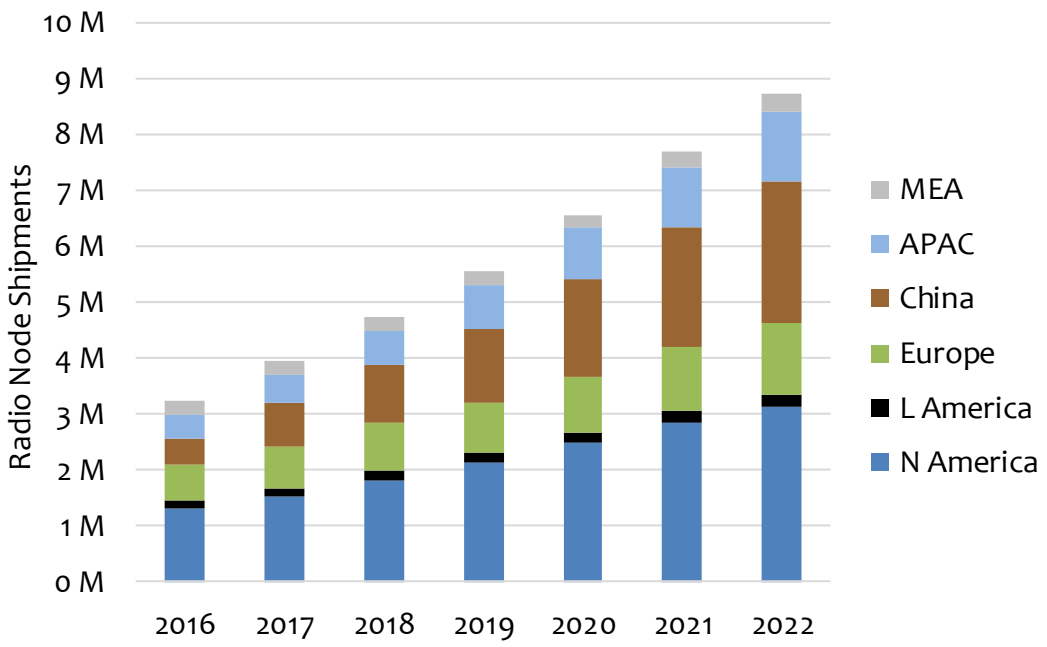
7. Enterprise IT Market: One of the key dynamics that drive the enterprise mobile infrastructure market is the maturity of enterprise IT market overall. Many enterprises in Western countries have traditionally relied on their own IT staffs and ecosystem of networking suppliers like Cisco to develop IT-centric products for in-building telecom needs. For example, Wi-Fi is a good example of enterprise-centric wireless technology that has served the enterprise market very well over the past decade. In strong enterprise IT markets like the USA and Europe where many of the top global companies are based, enterprises will likely also expect mobile infrastructure products and solutions that can meet enterprise-specific and vertical industry needs in each of the regions.



Source: Mobile Experts

Figure 20. Direction of in-building investment in world regions

In summary, these factors greatly shape the use of in-building mobile infrastructure. Overall, some regions will support ongoing evolution of multi-operator technologies (such as DAS), while other regions are more suited to operator-led projects using Small Cells including RRH and DRS systems like Ericsson Radio Dot and Huawei's LampSite. Extremely low cost markets that remain highly coverage-driven will use low-cost repeaters to enhance indoor coverage instead of using Small Cells or DAS which are relatively high cost in both capex and opex basis.



Source: Mobile Experts

Chart 4: Enterprise In-Building Mobile Infrastructure Shipments, by region

The North American market represents more than 45% of the DAS market today due to the high number of eager system integrators and the building owner's insistence on multi-operator products. In North America, the operators have essentially built out almost all major sporting stadiums that they are willing to invest in. Operators are still investing in secondary big-building projects such as airports, but it's clear that American operators will be slowing down their investment in DAS and leaving more responsibility on the local enterprise. North America will be, by far, the biggest market for enterprise mobile infrastructure---due to the fluid ecosystem of vendors and a cultural willingness to try something new.

In Latin America, coverage issues still count more heavily than in North America, so products that address coverage (such as repeaters) should find fertile soil. Passive DAS systems are used in Latin America heavily to this day, with lighter DAS options in many cases for basic coverage instead of huge capacity. Some Latin American countries are dominated by one or two mobile operators (Mexico is a prime example with Telcel at 70% market share), so single-operator products such as small cells may be appropriate even in public buildings. The ecosystem of system integrators and installers is weak in Latin America, but growing. As key Latin American cities reach high density (Sao Paolo, Mexico City, Buenos Aires), we will see small cell solutions come into heavier use.

Northern and Western Europe is likely to follow the US model, with a slight delay in enterprise channel adoption and ecosystem maturity. Southern and Eastern Europe will see

smaller investments due to basic economics. Enterprise investments and business model development in the more dynamic northern area will eventually lead to similar investment in the south and east. In most European countries, at least two to three, sometimes four, operators compete aggressively, so multi-operator solutions will be important. However, some enterprises are willing to adopt solutions that only support top two operators to reduce the overall infrastructure cost. While we expect to see more direct investment by the enterprises, the main "drag" in market adoption continues to be mobile operators' (lack of) commitment to really open up the market for greater DAS proliferation and certified Small Cell channel sales.

In China, all three major operators are state-owned. Theoretically, one would think that common ownership would lead to friendly relations between the companies, but in fact these companies are bitter rivals. The high-level government is trying to force some asset sharing through the creation of China Tower, to replicate the efficiencies of shared towers in other countries. For in-building projects, we anticipate that the three operators will work independently in most cases. DAS systems have been deployed mostly for single-operator applications over the past six years. Shopping malls, airports, and other major public buildings are currently adopting DRS systems and small cells, with some decline in DAS sales this year. Culturally, the enterprise is not likely to invest heavily in the hardware in China, because the operators are making the investments currently, and in some ways, everyone sees the operator investments as a political government stimulus -- making the need for enterprise investment doubtful.

In Asia (excluding China), enterprise investment is a stronger possibility. In the Philippines, Indonesia, Malaysia, and India, poor coverage and capacity for 3G and LTE systems indoors will drive aggressive companies to invest in small cells. Passive DAS systems are often used today, so there may also be some ongoing evolution of DAS in cases where multiple operators compete strongly in public buildings. Japanese and Korean operators have done an excellent job in covering most urban buildings, due to strong fiber availability and a highly competitive market. In Japan and Korea, we will see deployment of Remote Radio Heads by the operators, and less investment by the enterprises themselves.

In the Middle East and Africa, there are two outcomes: Rich economies such as UAE, Israel, and Saudi Arabia will have urban capacity issues, and concentration of market share should drive enterprises to invest in single-operator solutions. Poor economies such as Ethiopia, Libya, and Pakistan are less likely to see significant in-building investment, either by the operator or the enterprise. Mining operations, oil/gas facilities, and other major economic centers could be an exception, especially if IoT applications become critical to operations.

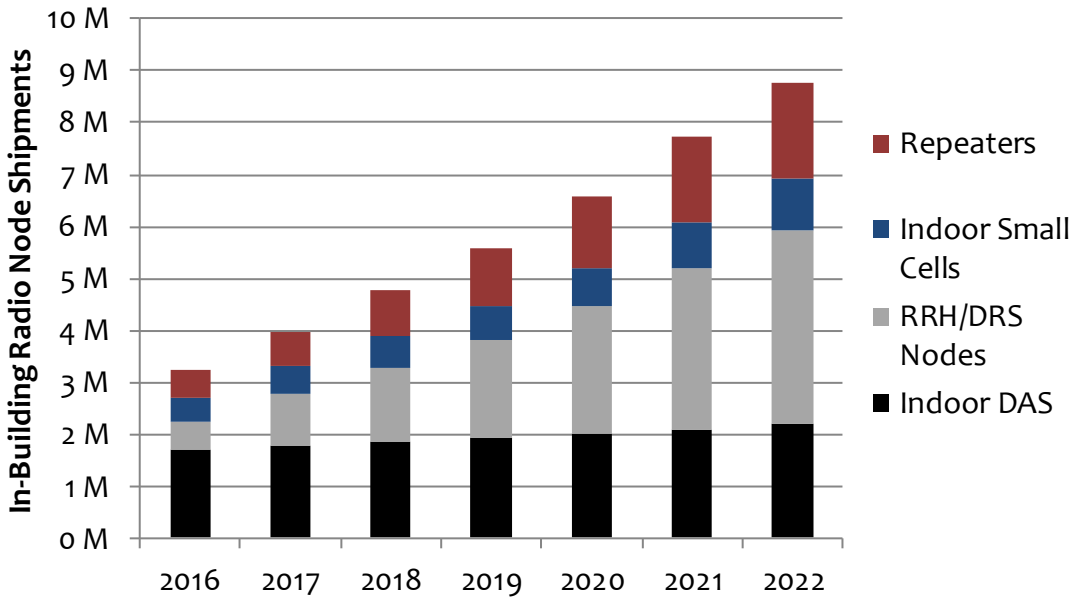
7 EQUIPMENT FORECAST

While the market for macro base stations has started its cyclical decline as broad LTE coverage buildouts have largely been completed in many of the developed markets in North America, Asia, Europe, the market for in-building mobile infrastructure continues to rise. The need for in-building mobile infrastructure is aided by new constructions and rising mobile capacity demand of enterprise customers, and both operators and enterprises are investing in mobile infrastructure hardware to outfit the buildings that they care about. For example, the operators are incentivized to invest in major public places like stadiums to tout their fast services to prevent churn, and major enterprises are forced to invest in robust indoor infrastructure to provide seamless mobile services to increase productivity of employees who increasingly rely on their smartphones for work communication and enterprise-specific applications on their devices.

This section provides a general overview of the shipment trends for each equipment type. A more thorough review of pricing, revenue, and market shares can be found in the Mobile Experts market studies for individual technologies, including *Small Cells*, *DAS*, and *Carrier Wi-Fi and LTE-U*.

Shipment Outlook

While DAS is the largest product segment of enterprise in-building mobile infrastructure deployments today (and revenue share at 70% of total enterprise mobile infrastructure market), the future growth will come from Small Cells. The strongest element will be the RRH/DRS systems that allow a cost-effective solution for enterprises looking for single-operator support to suit immediate needs. All product segments will grow over the next few years – some faster than others.



Note: includes enterprise-driven/targeted in-building radio nodes by both operators and enterprises

Source: Mobile Experts

Chart 5: In-Building Radio Node Shipments, DAS vs Small Cell vs Repeater, 2016-2022

DAS is a mature product segment and is largely targeted for large public venues requiring multi-operator support and extensible multi-technology, multi-band operation. The number of DAS node deployments will grow at a low single digit, fueled by major new construction projects and upgrade cycles.

Small Cells including DRS/RRH systems like Ericsson Radio Dot and Huawei's LampSite will be the biggest growth category over the next few years, growing at over 35% year over year. Mobile Experts forecasts that the number of DRS/RRH radio nodes will exceed 1M units in 2017, almost doubling from last year. In particular, we expect the growth to expand to Europe from a strong installed base in China and Asia. Also, Enterprise Small Cells targeting larger enterprises looking for scalable enterprise-centric deployment model and management capabilities like Spidercloud and Nokia will grow steadily at low-to-mid teens.

Repeaters will also see double-digit growth in low 20's as some niche market segments including low-density enterprise venues and light industrial complexes will be well-suited for extending mobile coverage indoors with repeaters without significant capacity load on macro base stations nearby. Mobile Experts believes that most light industrial enterprises are in non-urban settings and that nearby macro base stations are likely not heavily loaded today.

DAS Outlook

With tremendous product features to handle multiple frequency bands and multiple air interface technologies concurrently, DAS offers multi-operator support and robust flexibility that are inherently desired in large public venues with high traffic profile such as sporting venues where people are prone to consume and generate enormous amount of traffic. According to recent mobile traffic statistics from the Super Bowl held earlier this year, the top two operators, AT&T and Verizon combined, handles over 20TB of mobile data traffic during Super Bowl. While DAS remains most capable and flexible product for in-building mobile infrastructure system, the primary target market for DAS -- i.e., large public venues like stadiums and airports – is beginning to be tapped out. While new constructions and system upgrades every 3-5 years will continue to fuel DAS investments, Mobile Experts estimates that direct mobile operator investment will gradually decline over time.

Despite the decline in direct operator investment in DAS projects, some tech-savvy large enterprises are taking direct control of their mobile infrastructure needs. The decision to retrofit an enterprise campus is even more straightforward when it comes to new constructions. Planning ahead of new construction projects to install a DAS system can greatly enhance mobile work environment. As DAS suppliers revamp their product lines to suit the enterprise, reducing complexity and installation costs, we expect growing enterprise-driven deployments in hospitals, large hospitality venues and hi-rise class A buildings where robust mobile coverage can greatly enhance property value and attraction in those verticals. We are beginning to see a market introduction of "Embedded DAS" with small cell as a signal source that be sold as a single, pre-integrated solution to enterprises. Mobile Experts believes that these pre-integrated signal source DAS systems will be critical to widen the appeal of DAS systems to enterprises who lack the telecom expertise to directly interact with mobile operators.

Neutral host providers will continue to play a critical role in providing shared infrastructure economics for smaller enterprises who lack the will to make relatively large up-front investments and more importantly, the skillset to coordinate with mobile operators and manage the complex RF systems like DAS. Mobile Experts believes that the neutral host providers and some large enterprises will continue to drive the DAS radio node shipments at 4% CAGR from 1.7M indoor DAS nodes in 2016 to about 2.2M DAS nodes in 2022.

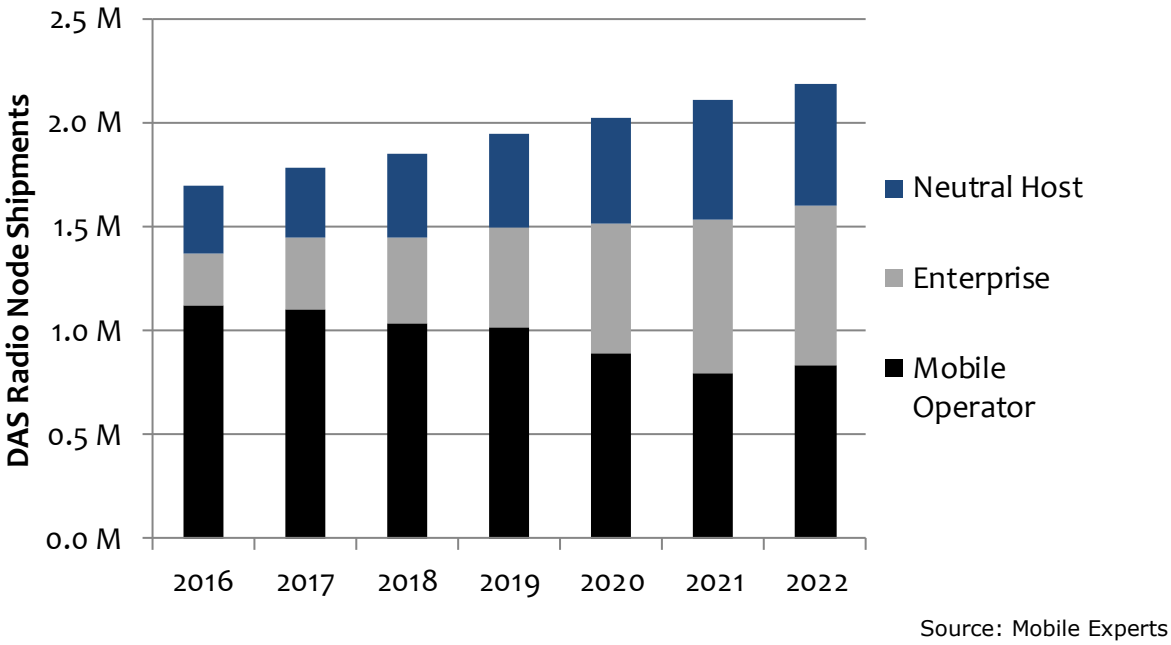
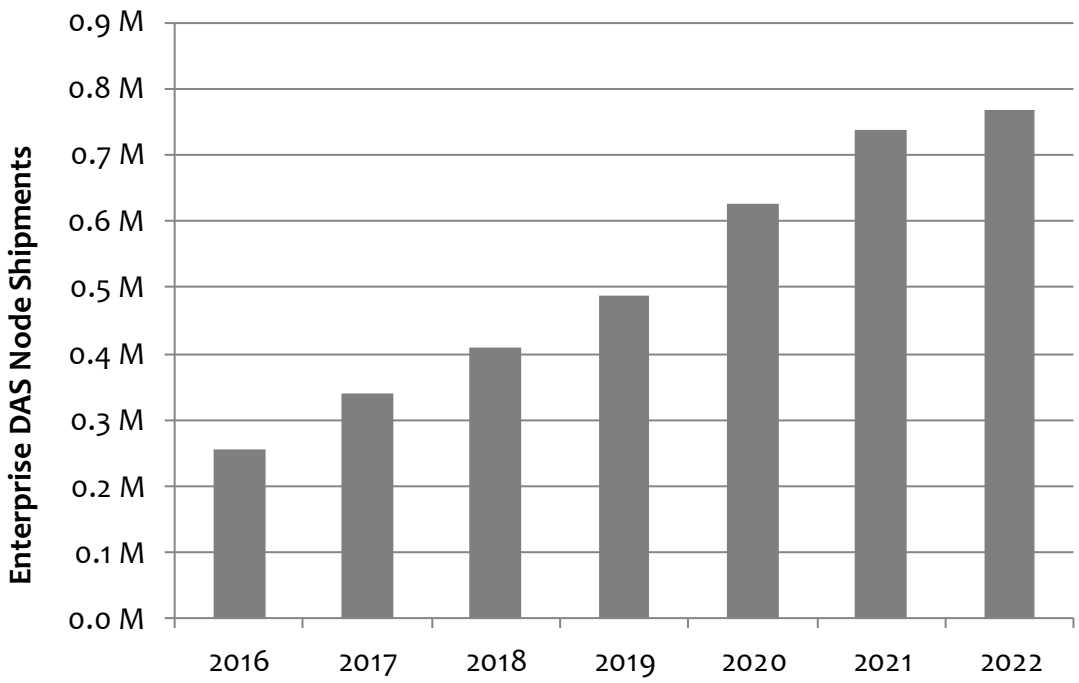


Chart 6: Indoor DAS Radio Node Shipment by Ownership, 2016-2022

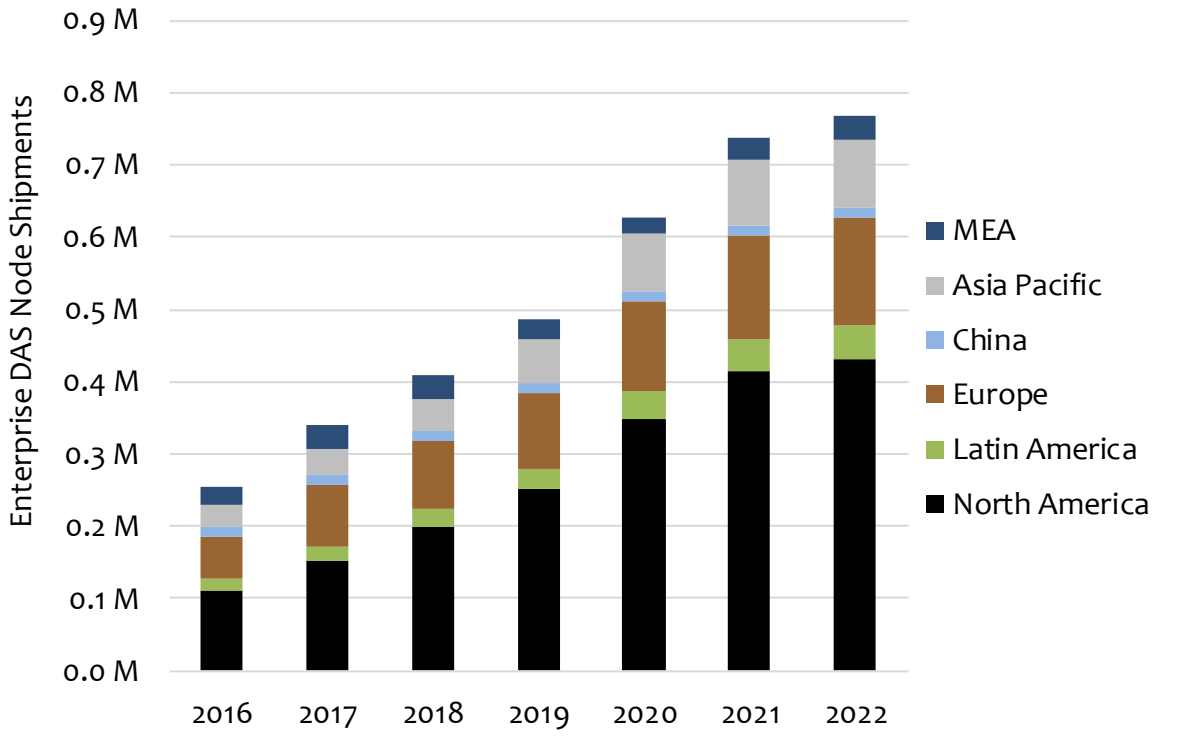
As DAS systems targeted for enterprise market continue to get simplified to reduce the overall cost, including installation and on-going management of the systems, Mobile Experts believes that an increasing number of enterprises may be open to deploying DAS systems that provide multi-operator support. Assuming that DAS suppliers are able to introduce cost-effective DAS systems that provide multi-operator support capability, even though initial deployments may only support one or two operators to reduce cost, Mobile Experts estimates that the Enterprise DAS market alone can grow at 20% CAGR from about 250K DAS nodes in 2016 to over 750K DAS nodes in 2022.



Source: Mobile Experts

Chart 7: Enterprise DAS Radio Node Shipments, 2016-2022

A bulk of the DAS market resides in the United States, primarily due to a strong ecosystem of system integrators and local value-added resellers that can assist with the complex process of regulatory permitting, mobile operator coordination of securing signal source, and a sundry of design, installation, and RF tuning processes that often complicate and perplex many enterprise organizations. The UK and a few Asian and European countries will follow with enterprise DAS deployments of their own. With the popularity of DRS and RRH deployments by mobile operators in China and Southeast Asia, the DAS market has not really developed in those regions, and Mobile Experts estimates that the DAS market traction in those regions to remain very limited.



Source: Mobile Experts

Chart 8: Enterprise DAS Radio Node Shipments, by Region, 2016-2022

Small Cell (DRS/RRH) Outlook

Small Cell shipments are growing quickly as detailed in our Small Cells report published earlier this year. Indoor small cells including Distributed Radio Systems (DRS) such as Ericsson Radio Dot and Huawei's LampSite are growing rapidly to address coverage and capacity demands indoors. For the enterprise mobile infrastructure market, we specifically highlight:

- *RRH/DRS* radio nodes often deployed by a mobile operator to address indoor coverage and capacity issues;
- *Enterprise Small Cells* targeting large enterprise (IT) customers; and,
- *SOHO Femtocells* that small home office customers can purchase directly from mobile operators to address indoor coverage issues at home or small office environments.

Mobile Experts estimates that about 10% of Femtocells are deployed for 'enterprise-driven' needs every year, and that Enterprise Small Cells are, by definition, 100% targeted for the enterprise market. While the bulk of DRS/RRH radio nodes are deployed by mobile operators today, we estimate that more and more of these units will be 'enterprise-driven' over time as DRS/RRH vendors position these units as a 'platform' for value-added services

such as location and advertising services. With the rapid uptake of DRS/RRH units like Huawei's LampSite in the past year, we expect the vendors to position the DRS/RRH units as enterprise products. This in turn will likely drive increasing enterprise adoption of these units as enterprise-specific application platforms to enable new services beyond simple wireless connectivity. Mobile Experts estimates that about 50% of DRS/RRH units in 2022 will enable or support enterprise-specific applications, thus driving enterprises to directly fund and (or through third-party integrator) deploy DRS deployment.

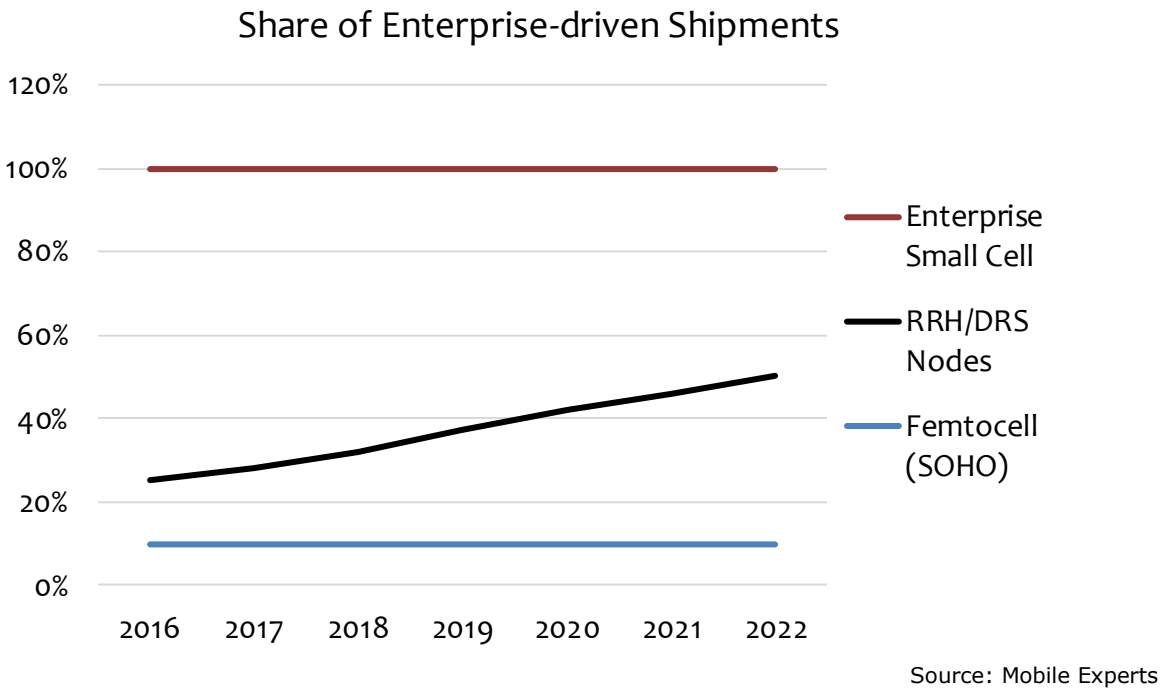
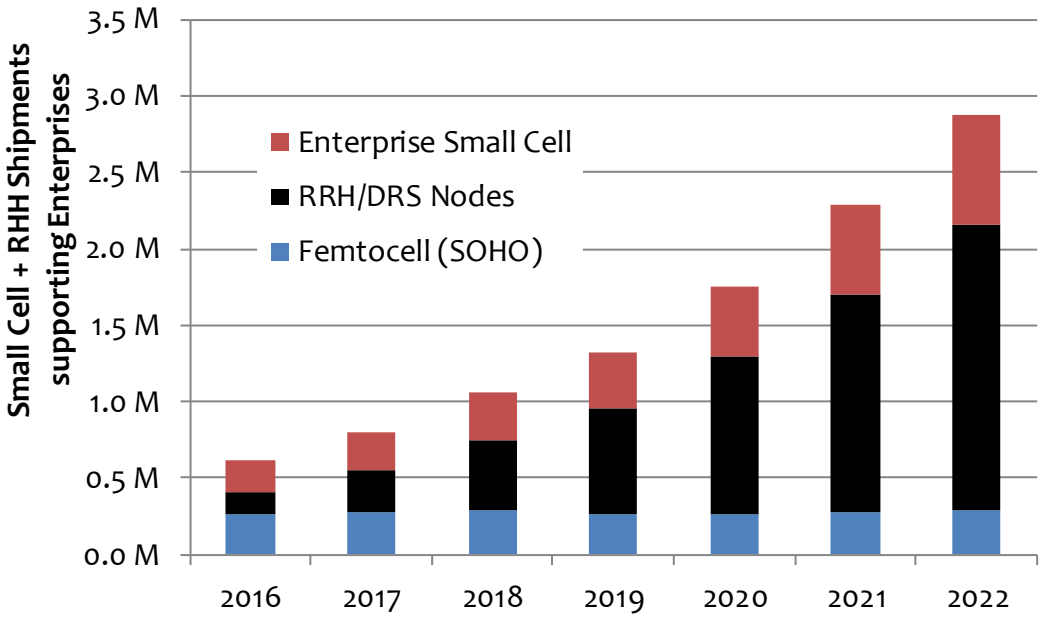


Chart 9: 'Enterprise-Driven' Share of In-Building Small Cell (RRH+DRS) Shipments, 2016-2022

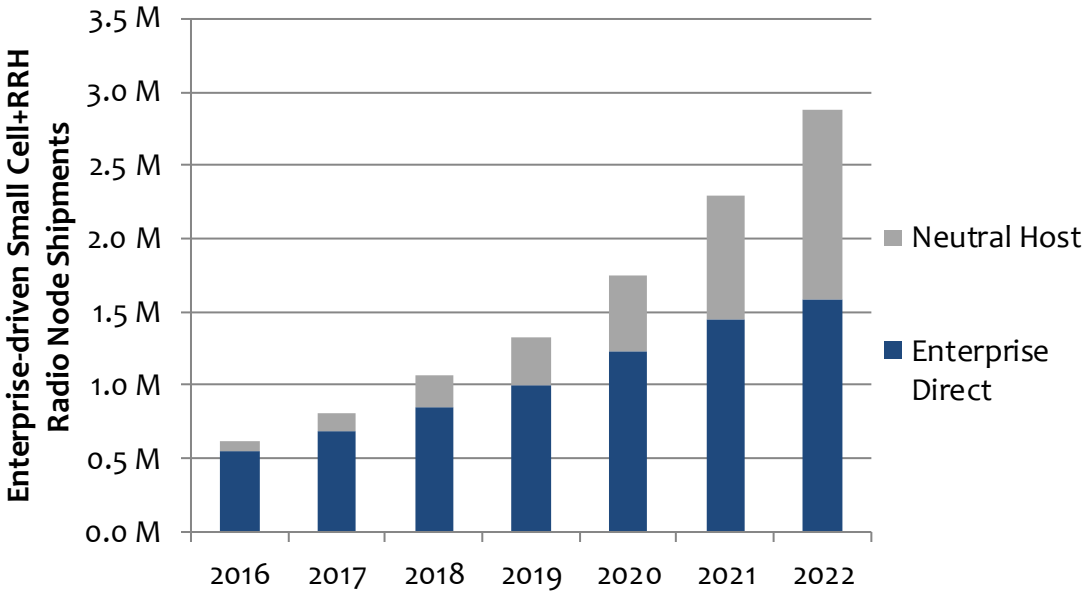
As enterprise-specific DRS platforms enable enterprise applications such as location and advertising services, we expect 'enterprise-driven' small cell shipments to rise dramatically from over 600K units in 2016 to over 2.8M units in 2022. With the scalability of deploying small cells where needed and operator preference for C-RAN architecture, Mobile Experts estimates that RRH/DRS shipment to far outpace the growth of other small cell products, specifically Enterprise Small Cells and SOHO Femtocells.



Source: Mobile Experts

Chart 10: Enterprise-Driven Small Cell (RRH/DRS/Integrated) Shipments, 2016-2022

As the market moves down market to smaller venues and enterprises, neutral host providers will play a bigger role in deployment of Small Cell radio units. Smaller enterprises will look to telecom-savvy neutral host providers to act on their behalf to design, install and manage Small Cell infrastructure and help coordinate network integration and connectivity with mobile operator core networks for seamless mobile connectivity in and out of buildings.



Source: Mobile Experts

Chart 11: Enterprise-Driven Small Cell/DRS Shipments, by Channel, 2016-2022

Small cells have strong operator support in Europe, China, Korea, Japan, and the USA. We expect balanced growth in multiple countries, although the flavor of small cell will depend on the backhaul options and operator competitiveness in each market. We expect that DRS systems will find enterprise-related success in China, Asia Pacific, Latin America, and Middle Eastern markets where Huawei has an installed base of customers. In many of these countries, local technicians do not have the skill level to integrate a small cell solution, so the macro vendor (Huawei or Ericsson) will be called in to handle the enterprise in-building solution.

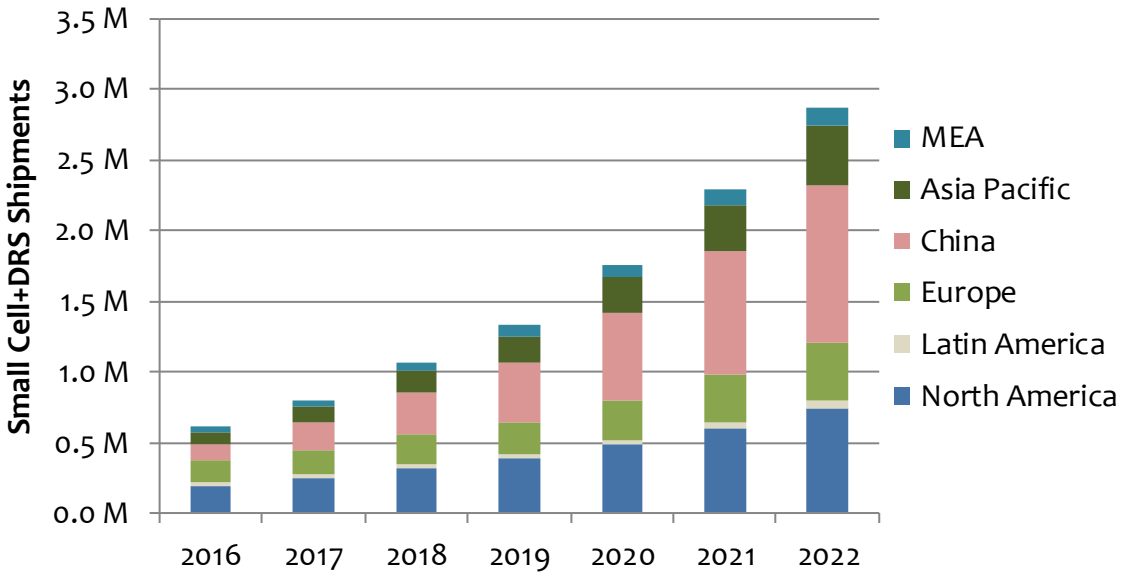
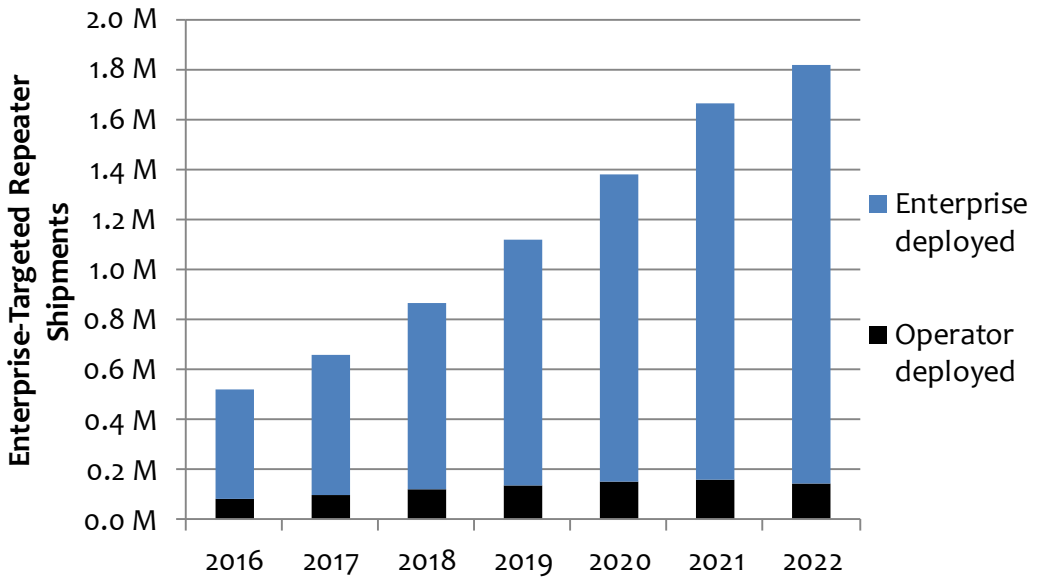


Chart 12: Enterprise-Driven Small Cell/DRS Shipments, by Region, 2016-2022

Repeater Outlook

In the last year's report, Mobile Experts focused on the operator-sanctioned "carrier repeaters" which have been approved by the FCC in the USA and being adopted in a few countries in other regions. In this year's report, we further segment the "carrier repeaters" based on who deploys the units. Mobile Experts estimates that a small portion of the "carrier repeaters" to be deployed by operators to satisfy indoor needs in rural and less-dense environments where macro base stations are lightly loaded – thus extending mobile coverage to handle indoor traffic via macro base station nearby won't negatively impact the macro network performance very much. In fact, it may perhaps be viewed as better utilization of macro network resources more effectively while providing good user experience indoors.

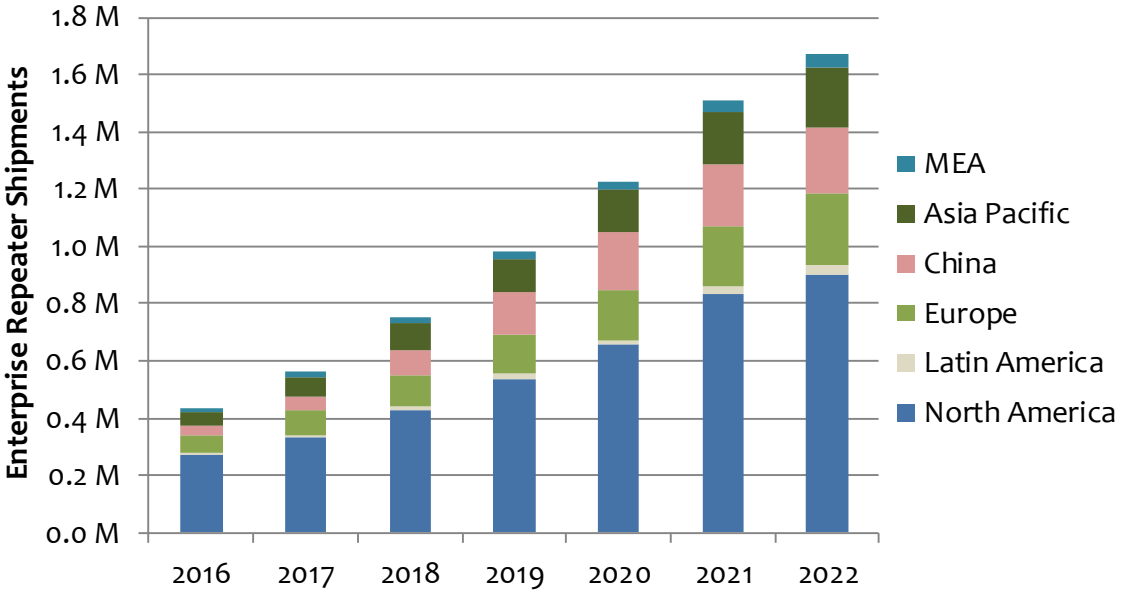
With ease of use and low cost, repeaters will be viewed as ideal solution for many enterprises. However, its use will be limited by the operators who will likely forbid its use in urban areas where traffic density is already very high and put strain on macro network performance. Where permitted, repeaters will find home for many enterprises looking to cover low-density venues especially those in rural areas with plenty of macro base station capacity. Mobile Experts estimates that between 80-90% of repeater units will be deployed by enterprises.



Source: Mobile Experts

Chart 13: Enterprise Repeater Shipments, 2013-2021

Repeaters are used all over the world. With the FCC ruling to allow operator-sanctioned devices to be sold legally, the repeater market has experienced strong growth in recent years. We expect that as the USA takes advantage of these "carrier repeaters", over time, other countries will begin to use repeaters increasingly as well.

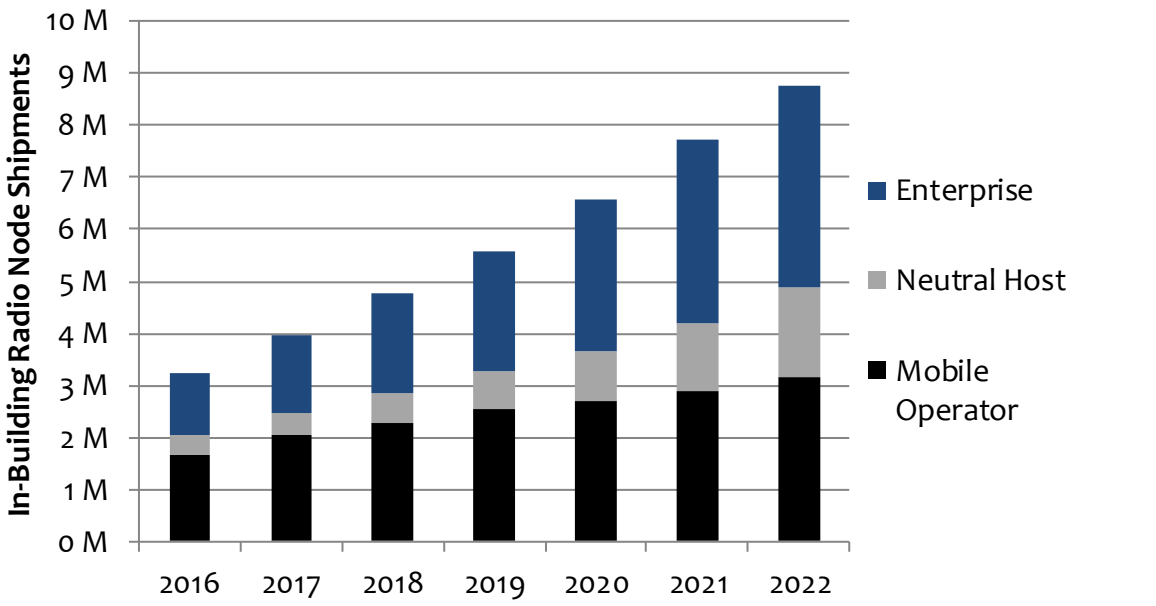


Source: Mobile Experts

Chart 14: Enterprise Repeater Shipments, by Region, 2013-2021

Business Model Outlook – Operator vs. Neutral Host vs. Enterprise-Direct Deployments

Today, over 60% of all in-building radio nodes are deployed by mobile operators either directly or indirectly through neutral host providers, primarily through DAS infrastructure to extend mobile coverage or increase data capacity indoors at marquee venues such as sports stadiums and major airports. With the mobile operators in developed markets focusing their attention towards 5G development and eventual deployment over the next several years, their capital allocation for in-building wireless projects is expected to be limited. Mobile Experts has observed limited operator interest or direct funding for in-building deployments beyond key public venues. With rising opportunity to address pent-up demand for mobile infrastructure, we expect neutral host network providers and large enterprises to directly fund and deploy in-building systems. With the complexity of deploying and maintaining mobile infrastructure systems that require coordination with multiple operators in region, Mobile Experts expect neutral host providers to play a key intermediary role in design, deployment and on-going maintenance of mobile infrastructure systems on behalf of enterprises going forward.



Source: Mobile Experts

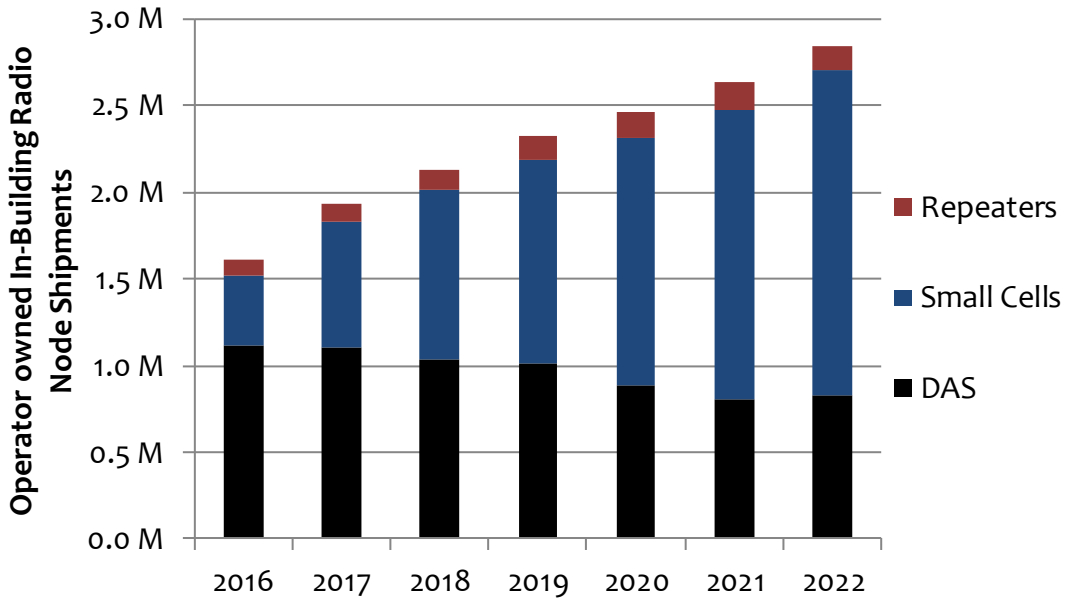
Chart 15: In-Building Radio Node Shipment by Ownership, 2016-2022

In-building wireless technology and product deployment differs by business stakeholders. Mobile operator requirement for in-building wireless system will certainly differ from small enterprises. Mobile operators will look for flexible systems that can support multiple air interface technologies and frequency bands that they operate, and demand control and management capabilities that are on par with very large macro RF network systems. Meanwhile, small enterprises will demand low-cost systems that are easy to deploy and

manage and provide seamless mobile voice and data services. These diverse requirements will drive different preferences for in-building systems.

Mobile operators are telecom-savvy experts and have relied on cost-efficient DAS systems for high-density, public venues like sporting stadiums and airports for years. As the small cells technology matures and provides control and management capability close on-par with their macro infrastructure, they will deploy small cells for smaller (but still large) enterprise venues like corporate campuses, high-rise buildings, etc. With scalable deployment capability and increasing availability of operator-approved enterprise small cells, Mobile Experts expects Small Cells, including DRS systems like Ericsson Dot and Huawei's LampSite, to be deployed by the mobile operators in increasing numbers, raising its share of radio node shipment from 25% of total mobile operator in-building radio node deployments in 2016 to 66% in 2022.

While the mobile operator deployment of in-building radio nodes will continue to increase at about 10% CAGR over the forecast period from 2016 to 2022, we expect the number of mobile operator owned DAS nodes to decline at 5% CAGR while the Small Cell radio nodes to grow at almost 30% CAGR. Operators will selectively deploy repeaters to extend mobile coverage in key enterprises in places where nearby macro base stations are not heavily loaded.

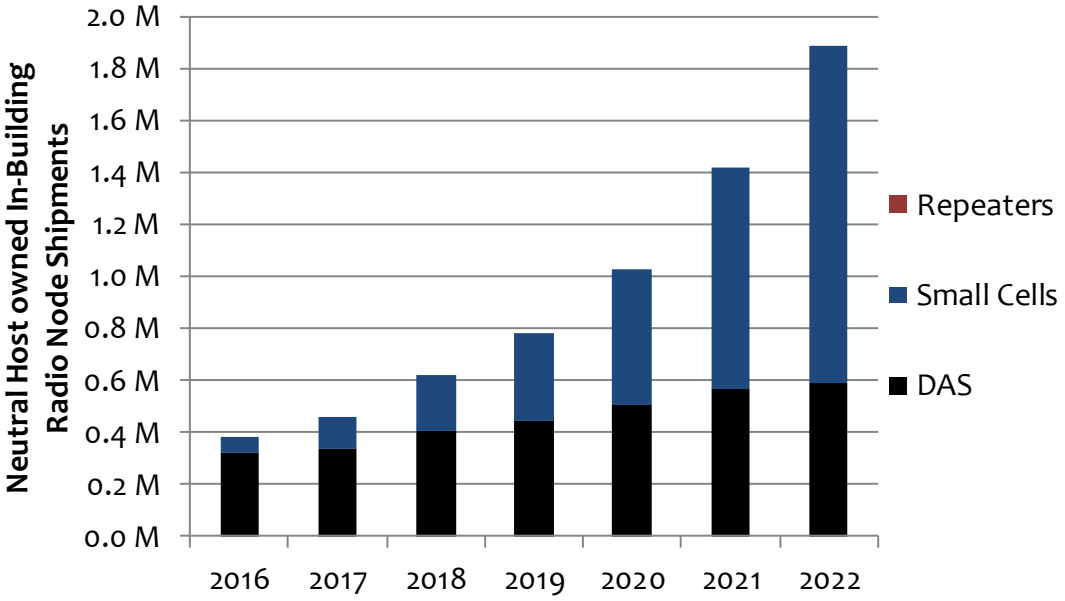


Source: Mobile Experts

Chart 16: Mobile Operator-owned In-Building Radio Node Shipment by Product, 2016-2022

Neutral host providers play an important role in the telecommunication infrastructure market. Players like Crown Castle, American Tower, Extenet and others enable a shared infrastructure business model that lowers a burden for the high fixed-cost industry at large.

Today, the majority of neutral host providers focus on very large public venues like stadiums, airports, and hi-rise commercial buildings that are of interest to mobile operators and large enterprises with big "purse strings". As the players begin to address large numbers of smaller venues across other vertical industries such as hospitality, healthcare, commercial real estate, etc., we expect the neutral host providers to address some of the smaller venue opportunities with Small Cells and cost-effective "light" DAS systems. Mobile Experts expects the neutral host providers to continue to deploy increasing number of DAS nodes at over 10% CAGR while significantly expanding the Small Cells deployment at over 60% CAGR during the forecast period. The in-building radio node deployment by neutral host providers is expected to see the greatest increase in comparison to the mobile operator or direct enterprise deployments.

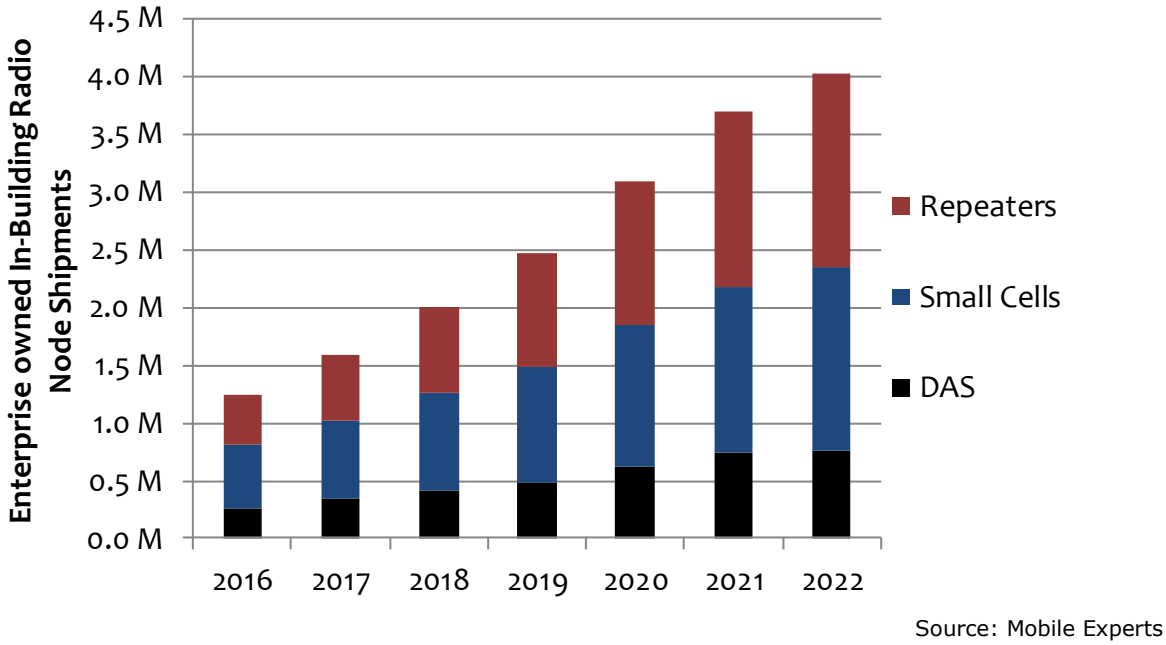


Source: Mobile Experts

Chart 17: Neutral Host-owned In-Building Radio Node Shipment by Product, 2016-2022

Enterprises range from a SOHO enterprise with one or two workers working out of small commercial spaces to an international conglomerate with tens of thousands of workers in corporate headquarter office environments worldwide. This wide range of enterprises naturally results in a variety of in-building mobile infrastructure products addressing this diverse market. While small SOHO enterprises may be fine with SOHO-targeted Femtocells connected to high-speed Internet for backhaul, very large enterprises with hi-rise buildings or large campus environment may require large DAS systems or network of Enterprise Small Cells that enable seamless mobile services in and out of campus environments, as well as enabling enterprise-specific applications over those networks. Mobile Experts estimates that about 250-300K SOHO Femtocells, sourced directly from mobile operators, are deployed directly by very small enterprises annually. Also, we estimate that some small enterprises and light industrial enterprises with large warehouse-like venues with limited

mobile usage are deploying repeaters to extend macro coverage indoors. Large enterprises with high mobile usage, public-facing venues, and requiring critical reliance on mobile connectivity (e.g., hospitals) will continue to rely on DAS systems that can provide a multi-operator, mobile coverage/capacity solution. With growing demand across various vertical segments, large and small, Mobile Experts expects about 20% CAGR growth across the DAS, Small Cell, and Repeater product segments.



Source: Mobile Experts

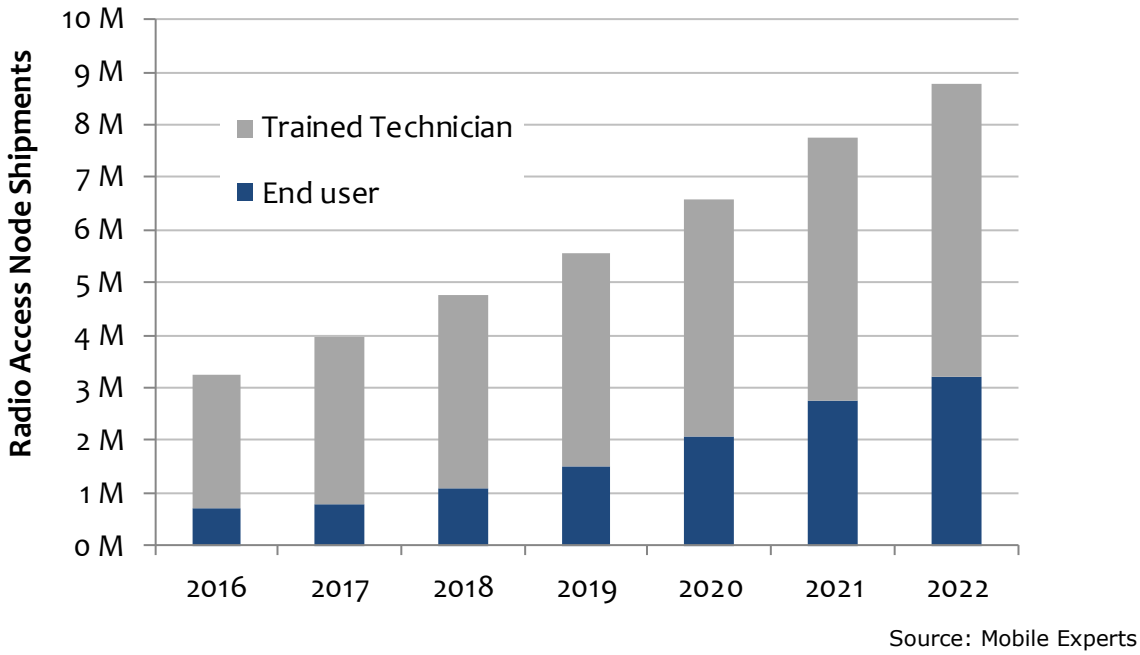
Chart 18: Enterprise-owned In-Building Radio Node Shipment by Product, 2016-2022

Outlook for Self-Installation

DAS and non-residential Enterprise Small Cells have always been installed by highly trained technicians. These complex systems require careful RF planning and design, careful measurements, walk-through testing, and configuration management, that is tough to master for traditional IT staff. Today's small cells and 2018 "Embedded DAS" systems are expected to take care of auto-configuration, so the outlook is bright for simplified enterprise products that can be sold to a corporate IT departments directly and self-installed.

Today, the bulk of "self-installable" enterprise mobile infrastructure product is made up of small office/home office (SOHO) targeted Femtocells that home office enterprise customers can purchase directly from mobile operators to enhance mobile coverage in home and small enterprise environments where macro base station coverage is weak. For larger enterprises, Mobile Experts expects Enterprise Small Cell and "Embedded DAS" will develop product features to ease installation and provisioning processes, which will further increase

the appeal of these products to enterprise IT customers. In particular, we believe that CBRS will be self-installed for many vertical market segments… similar to Wi-Fi.



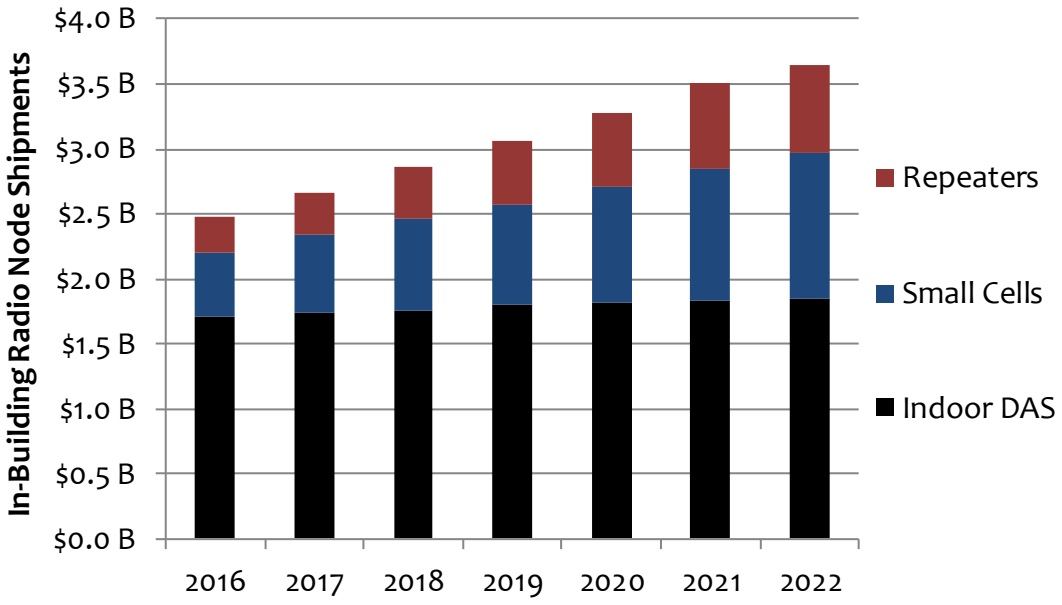
Source: Mobile Experts

Chart 19: Enterprise Mobile Infrastructure Revenue Outlook, 2016-2022

Over the course of our forecast period, Mobile Experts expects over 60% of mobile infrastructure radio nodes to be deployed by trained technicians and that neutral host providers and telecom-focused system integrators will increasingly address the enterprise needs in mobile infrastructure.

8 REVENUE FORECAST

The enterprise in-building mobile infrastructure market is dominated by DAS as they hold the premium tier of the market. As the enterprise mobile infrastructure market expands "down market" to address smaller venues and introduce products targeting enterprise-purpose applications, Mobile Experts expects small cell products, including RRHs and DRS systems (e.g., Huawei's LampSite and Ericsson's Radio Dot), to drive the overall market outlook in terms of revenue. Meanwhile, the repeater market is expected to constitute about 10% of the overall market, largely targeting smaller enterprises and lower-density venues.



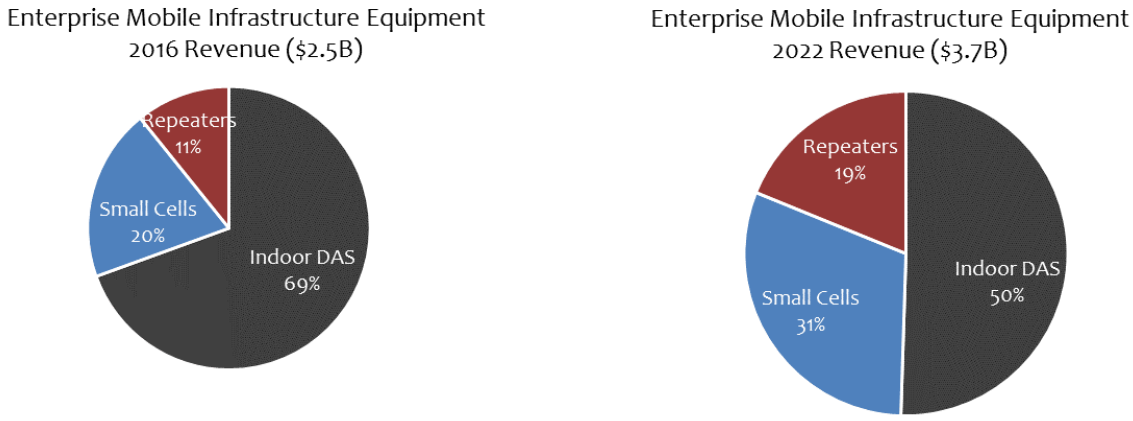
Source: Mobile Experts

Chart 20: Enterprise Mobile Infrastructure Revenue Outlook, 2016-2022

Mobile Experts forecasts the overall Enterprise Mobile Infrastructure market to grow from about $2.5B in 2016 to $3.5B in 2022.

- The DAS market segment is expected to grow in low single digits to constitute about $1.84B in 2022.
- The Small Cells market segment including DRS and RRH radio units to grow at 13% annually from under $490M in 2016 to $1.02B in 2022.
- Lastly, the Repeater market segment is expected to grow from about $270M in 2016 to about $680M in 2022.

As the enterprise mobile infrastructure market expands beyond the marquee venues to smaller enterprises, Small Cells and Repeaters will make up increasing share of the market, growing from a combined 30% of the total enterprise mobile infrastructure equipment revenue in 2016 to almost 50% in 2022.



Source: Mobile Experts

Chart 21: Enterprise Mobile Infrastructure Revenue Share by Product, 2016 to 2022

9 COMPANY PROFILES

Accelleran

Accelleran is a small cell OEM start up based out of Belgium focusing efforts to produce LTE TDD small cells, targeting both licensed bands and shared 3.5GHz CBRS band for the US. At MWC 2017, the company released its CBRS small cell based on Cavium SoC. The company has a few trials ongoing with cable and OTT operators in the US to pursue potential market opportunities leveraging CBRS, possibly for enterprise indoor applications.

ADRF (Advanced RF Technologies, Inc)

ADRF is an established in-building systems and services company with headquarters in Burbank, CA. It has expanded as a supplier, with DAS solutions in addition to their previous repeater products. AT&T has used the company for high profile projects such as Disney Parks and the Fox Theater in Atlanta. Verizon has also named ADRF as one of its primary DAS vendors, increasing the company's profile with most of the major mobile operators in the US.

Airspan

Airspan Networks has developed a line of LTE small cells, including indoor enterprise units and outdoor units with integrated wireless backhaul. The company introduced LTE Relay systems to boost network efficiency at cell edge. The company has deployed tens of thousands of small cells with Reliance Jio in India, as well as successful relationships with Softbank in Japan and with Sprint in the US. With successful small cell deployments, the company has tripled its employee base to pursue growing opportunities in North America, APAC and MEA.

American Tower Corp

American Tower provides in-building DAS services to more than 1300 buildings in North America, as well as their primary business in leasing tower properties worldwide. The company targets enterprise customers in specific vertical markets such as airports, hospitality, and healthcare markets, and claims to operate more in-building DAS networks than any other neutral host provider. The company's main business centers on the operation of a large number of macro cell towers, so the company has strong relationships with mobile operators in the USA and growth prospects internationally.

Argela

Argela has close connections with Turkish mobile operators. As a part of Turk Telekom Group, Argela has a more direct route to market than other femtocell suppliers. The company has developed a line of 3G and LTE small cells, which has had only limited success

on the wider market. The company works with Altobridge for small cells for 3G in rural deployment and they have partnerships with Cisco and NEC for gateways. Recently, the company demonstrated its ProgRAN solution that encompasses the programmable RAN solution based on the NFV/SDN principles based on Cavium's baseband processor platform.

Aruba (acquired by HP Enterprise)

Aruba was acquired by HP in May 2015 to provide technology for converged campus solutions. Aruba provides Enterprise Wi-Fi network equipment and related software solutions, including indoor and outdoor campus solutions. Aruba has put more focus into service provider support during the past year, and engages in stadiums and other large venues with various operators. Aruba has been gaining share in the Carrier Wi-Fi space with touted differentiation around security backend.

Baicells

Founded in 2014, Baicells is a privately-held company based in Beijing, China. The company's product solutions range from indoor and outdoor small cells, CPEs, and antennas. With a new sales office in the US, the company is expanding into unlicensed and shared spectrum opportunities with cable operators and neutral host providers. The company announced its 'NeutralCell' small cell product at MWC 2017 leveraging 3.5 GHz CBRS.

Bird Technologies (DeltaNode)

Bird Technologies, a leading RF test and measurements company acquired DeltaNode in 2013, so DeltaNode now operates as a subsidiary of Bird known as Deltanode Wireless Technology, and operates fairly independently. Launched in 2005 to offer repeaters and related products to wireless operators, DeltaNode has been successful in selling fiber-fed DAS systems in the United States. DeltaNode offers radio heads with power levels up to 20W, and in particular has been able to secure contracts for DAS coverage of highways, railways, and other mobility applications. In general, DeltaNode is most successful in promoting outdoor DAS products or in projects with a mix of indoor and outdoor elements.

Black Box Network Services

Black Box acquired Inner Wireless in late 2012 and together they have focused intently on support of multimode DAS systems for enterprise applications. Healthcare is a particular focus for the company, but they have also branched out into major projects in office buildings and sporting venues as well. With a recent CEO change, the company may be going through a strategic change as a broader IT infrastructure and solution provider.

Boingo

Boingo runs Hotspot 2.0 networks in several airports and continues in the Wi-Fi business, but has also reinvented itself as a DAS/Small Cell neutral host, and currently has more than 7600 DAS nodes in operation. Boingo has focused on US military bases as an interesting market segment. The company has multi-technology deployments using DAS, Small Cells, and Wi-Fi, and is exploring further neutral host deployments using all available technologies.

Bravo Tech Inc/BTI Wireless

Founded in 1999, BTI has grown from a small amplifier supplier to become a supplier of in-building repeater systems, outdoor DAS systems, remote radio heads, and small cells. Bravotech has major facilities in Southern California and Shenzen, China, and retains over 800 employees. The company has a poor reputation for quality in the North American market, but has been quite successful in Asia with linearized amplifiers and repeater products. Bravotech is considered a low-price supplier in the US market.

Cisco

Cisco's global footprint and channel sale partnerships especially in enterprise IT segment bodes well for its small cell solutions. Cisco has been working to arrange the business conditions for mobile operators and enterprises to support the upgrade from Wi-Fi to licensed/unlicensed operation. Endorsements from several tier-one mobile operators including Vodafone and EE have validated the Cisco enterprise approach. Cisco's strategic partnerships with SpiderCloud for enterprise small cell segment and also with the larger Ericsson partnership bolds well for its wider aspiration to increase share in the service provider segment, and small cell is expected to be a meaningful part of its offering to service providers. Cisco's "direct-to-enterprise" small cell strategy appears to have changed recently, as it plans to open its clip-on interface to small cell partners instead. Cisco's wireless strategy is still largely an extension of their Wi-Fi and IEEE 802.11 roadmap.

ClearSky Technologies

This Florida-based company provides hosted infrastructure and services to tier-two and tier-three mobile operators, primarily in the US. The company has recently announced its contract with GCI, a leading mobile operator in Alaska, to provide a complete small cell as service solution offering.

Cobham Wireless

Cobham Wireless was formed in early 2015 by combining Axell Wireless acquired in 2013, with Aeroflex, which Cobham acquired in 2014. The rationale is that the test and measurement assets and expertise of Aeroflex would provide synergies to the combined company. Axell holds a strong market share in the European DAS market, with unique

products that are tailored for high mobility coverage in tunnels and remote areas. Axell routinely integrates public safety radio with digital repeaters, and has started shifting slowly from passive to active DAS in their everyday deployments. Axell also provides DAS for some high-density applications such as stadiums in Europe. The company has introduced a product called "Intelligent digital DAS" (idDAS) which allows for dynamic capacity allocation similar to other new flexible DAS architectures. The company has recently gone through a major re-organization with changes in executive management.

Comba Telecom

Comba is the main DAS supplier in China and other cost-sensitive markets. The company has recently focused on Latin America with several stadium deployments. The company has also worked together with top tier OEMs in deployment of radio heads for high-density indoor/outdoor applications. The company supplies a wide range of repeaters, DAS radio heads, TMAs, residential and indoor small cells, and other coverage related products. Their use of repeaters together with DAS has resulted in some low cost "Light DAS" projects that defy the cost position of other vendors. Comba is late in developing enterprise DAS products because they're not strong in the USA or European markets.

Commscope

Commscope is a strong competitor in both indoor and outdoor DAS markets, with multi-operator products tailored for both market segments. As one of the world's leading cable suppliers, Commscope can offer a bundle with DAS equipment, antennas, and cabling to address the entire DAS material requirement. The company has recently introduced a solution called ION-E which provides in-building DAS coverage without duplexers in the radio head, allowing for very flexible operation. With recent acquisitions of TE Connectivity and Airvana, Commscope's indoor and outdoor mobile infrastructure product set has increased extensively ranging from fiber optic connectivity, DAS, and small cells. With the Airvana acquisition in 2015, Commscope has formally introduced a small cell product based on Airvana's OneCell. The OneCell concept combines aspects of small cells, DAS, and Cloud RAN to create a flexible in-building solution that can dynamically allocate capacity throughout a building, while avoiding some of the high cost items associated with DAS, and providing CRAN features such as CoMP and eICIC.

Communications Components Inc.

CCI, based in New Jersey, USA, directly supports mobile operators for unique coverage challenges. CCI's primary business was built on co-siting and combining products for 2G/3G networks. CCI also offers a line of bi-directional amplifiers and DAS interface units for in-building applications, and has been very successful with major carriers such as Verizon and AT&T, working as a system integrator to pull together DAS and RF solutions.

Connectivity Wireless

Connectivity Wireless is a prototypical system integrator/solution services company that specializes in full DAS design, deployment services to multiple vertical sectors, including hospitality, hospitals, stadium and commercial buildings. With over 2000 DAS deployment projects under its "belt", the company has seen a rapid growth.

Consistel

Consistel is a system integrator based in Singapore, with operations in Pakistan, Philippines, Indonesia, Malaysia, and Thailand as well. The company has done well to dominate the Singaporean market with more than 3000 enterprise DAS projects, most of which use passive DAS. Although it had shown its aspiration to become a fourth operator in Singapore, its fate and energy appears to be focused on being a wireless software solutions and system integrator.

Contela

Contela provides femtocells and related gateways for the Japanese and Korean markets, and has ramped to significant volume with more than 80,000 LTE small cells for SK Telecom. The company has been able to successfully penetrate at least two major customers outside of the Korean market, with significant shipments during 2015. The company has a partnership with Hitachi Communications Technologies America, to use the Hitachi gateway with the Contela access point.

Corning

Corning acquired fast-growing MobileAccess in 2011 and has continued the company's strong push into in-building DAS systems, of course combined with Corning's optical fiber. Corning serves enterprise customers, neutral hosts, and a few operators with in-building distribution systems. Their latest DAS product uses CAT-5e/6 cable inside the building to distribute mobile signals in the case of newer standards, and simple RG6 coaxial cable for smaller buildings. Corning has had some success with retail malls, hospitals, and hi-rise office applications. Its ONE Wireless platform supports both Wi-Fi and cellular on a single platform.

Crown Castle International

The company has made several fiber acquisitions in the US to bolster its small cells business by offering both backhaul transport (primarily dark fiber) and site leases for mobile operator customers to deploy small cells or outdoor DAS remote radio heads in key markets. Through these acquisitions, the company has become a market leader in DAS neutral hosting, for stadiums and university applications with both indoor and outdoor components. The company's wireless infrastructure consists of 40,000 towers and 17,000 route miles of fiber.

As of 2016, the company reports that its small cell infrastructure business now make up about 10% of its total business, and continues to report upside momentum in its small cells business.

CS Corporation

CS sells repeaters in the Korean market and worked closely with SKT in the 2012-2013 timeframe to implement a customized stack and a small cell hardware solution. The company shipped significant volumes of LTE small cells to SK Telecom in 2012, but has not reached beyond this one opportunity in small cells. The company lists mobile communication as one of its wide range of businesses including digital broadcast, battery systems, and government electronics.

Dali Wireless

Dali offers a distributed radio system with dynamic capacity allocation, essentially making RF "routable" like an IP router. The company has focused on patents, with more than 250 patents filed, many of which relate to the use of CPRI and other IP formats to implement adaptive traffic capacity in DAS. The company has some interesting enterprise installations such as the Hilton in Los Angeles and the Dallas/Fort Worth Airport.

Ericsson AB

Ericsson showed up late to the small cell party, but they quickly took a leadership position in high-end small cells. The RBS6402 product incorporates 10 frequency bands with up to four running simultaneously, as well as integrated dual-band Wi-Fi. By offering a standard product with carrier aggregation and macro parity, Ericsson has established a gold standard in the high-end small cell market. Ericsson also offers the "Radio Dot" product as an approach for medium-sized enterprises. Ericsson's biggest move in the small cell market came with the news of its acquisition of BelAir Networks in March 2012. The combination of strong Carrier Wi-Fi and licensed-band small cell capability puts Ericsson in position to support converged small cells. With the recent Ericsson re-organization in March 2017, and ongoing Cisco partnership, it remains to be seen whether there will be a focused organizational business unit dedicated to small cell products.

Extenet Systems

Extenet Systems is a privately-held wireless infrastructure provider of distributed networks. As a part of broader Digital Bridge holdings, the company designs, owns, and operates neutral-host networks leveraging multiple technologies including small cells, Wi-Fi, RRH, DAS, and other technologies on behalf of mobile operators and enterprise customers. The company recently partnered with Verizon to build out some of Verizon's small cell deployments in the San Francisco bay area. The company has ongoing projects with many of

tier 1 operators in the United States. Some notable installations in high-rise buildings include Sears Tower, Trump Tower and the Empire State Building as well as several sports arenas.

Extreme Networks

With a heritage in Ethernet switching and routing, Extreme networks has had some success deploying its networking gear along with Motorola Enterprise Wi-Fi access points into several NFL stadiums, including Gilette in MA, Philadelphia Eagles stadium, and others. Also leveraging the moniker as an official Wi-Fi analytics provider of NFL, it has received several bid wins in other verticals. The company continues to bolster its product portfolio with a planned acquisition of Brocade's data center product/business from Broadcom.

Fiber-Span

Fiber-Span has been supplying DAS using RF over fiber for many years, and has grown to a mid-sized supplier through focus on the public safety market and related government contracts, as well as some high-profile DAS projects such as the NYC subway. Fiber-Span launched a partnership with TE Connectivity during 2014 which helps the company to offer a more complete product line for indoor-outdoor deployments. Recently, it has partnered with Corning to serve up its public safety system as a part of Corning's ONE system.

Goodman Networks

Goodman Networks offers turnkey services for installation of DAS, Small Cells, repeaters, and other in-building wireless solutions. The company has grown with the acquisition of Cellular Specialties and then Multiband over the past two years, making Goodman one of the bigger wireless system integrators in the US> The company has been involved in all of the last five American Super Bowl wireless deployments.

Huawei Technologies

Huawei is a shipment leader in non-residential small cells with success of its LampSite product line. The first two generations of LampSite, which can best be described as a low power RRH product with distributed RF, has been hugely popular in China and Southeast Asia. The product provides flexible indoor coverage/capacity solution with 'macro parity' features so that operators can reduce operational and management costs associated with running multi-layer networks. The company has focused its efforts on multi-band small cells for higher capacity carrier applications. With the next-generation LampSite, Huawei is targeting other regions including Europe where RAN sharing is more common.

IBWave (acquired by Corning)

IBWave provides modeling and planning services and software tools for mobile operators to develop in-building solutions. The IBWave database includes DAS solutions, small cells, repeaters, and most recently Wi-Fi as a comprehensive tool kit to plan a wide variety of in-building options. With Corning's acquisition in 2015, it is now a wholly-owned subsidiary of Corning Optical Communications business unit.

Innowireless (Qucell)

Based in Korea, Innowireless provides network testing and optimization solutions. Most of their revenue is derived from testing/optimization services in North America. The company delivered tens of thousands of small cells to Korea Telecom for their LTE capacity upgrades during 2012 and 2013, acting as an ODM with a Cavium chipset and using software developed by third parties and by KT themselves. Recently, the company, under the "Qucell" brand, has been introducing both FD-LTE and TD-LTE residential, indoor, and outdoor small cells based on Qualcomm chipset to KT, Fujitsu and others.

ip.access

Femtocell vendor ip.access has successfully penetrated the enterprise and rural/remote markets, as well as its longstanding residential success with AT&T Wireless and a few other mobile operators. With a recent investment from a private equity and several product introductions, including LTE access points covering more frequency bands to cover more markets, and the Viper platform to ease the enterprise small cell deployments, the company is looking to accelerate its growth. In a competitive marketplace with similar marketing messages around virtualized RAN with ease of deployments, it will likely come down to robust product features and tactical executions.

JMA Wireless

JMA acquired Italy-based Teko Telecom in 2013, and since then has been successful in penetrating the US market for stadium DAS. JMA/Teko installed major DAS systems in stadiums in Philadelphia and Santa Clara within the first year. The company is also highly focused on the hospitality market.

Juni Networks

With a research and development center in Korea, Juni has been developing LTE small cells based on Intel platform since 2009. It is focusing on CBRS market and has a trial ongoing in this space.

Kathrein

Kathrein has a long track record of bringing high-quality antennas and other products in the outdoor macro market. Kathrein introduced its K-BOW DAS system in 2014 and recently has installed the system in a commercial field application for some enterprises.

MER Telecom Group

Based in Israel, MER Telecom is a tower company that acquired CellO Wireless in February 2014 as a way to diversity and offer in-building DAS solutions. Their DAS operations remain pretty small today.

Mobilitie

Mobilitie is one of the largest private wireless infrastructure providers in the US. After selling outdoor tower assets to SBA in 2012, it has funded, designed and operate several large in-building projects along with some outdoor deployments. It provides wireless infrastructure, in some key sporting venues, including the Verizon Center in DC, Arrowhead Stadium, Churchill Downs and many other venues. In many cases the company takes the role of a neutral host, providing the funding for initial deployment. Recently the company has been associated with Sprint's small cell deployments.

NEC

NEC has successfully deployed significant numbers of indoor and outdoor small cells for Softbank and other operators in Japan, but outside of Japan the company focuses more on the gateway. NEC sells a femtocell Node B for HSPA applications using the I-uh standard, but has also developed an IMS-based femtocell for Softbank's deployment in Japan. NEC has successfully partnered with SpiderCloud to offer 3G/LTE and LTE-LAA solutions for the enterprise segment. NEC has partnerships with Netgear and Cisco, as well as core network integration relationships with Kineto, Tatara Systems, and Genband. The company has fairly mature LTE outdoor small cell products and lower cost in-building solutions for enterprise. NEC's challenges are in cost and marketing to international operators.

Nextivity

Founded in 2007 and based in San Diego, CA, Nextivity supplies high-performance carrier-specific repeaters that are designed to coexist with macro networks without interference. The company has been "authorized" by 179 mobile operators worldwide and has products certified by the FCC. As one example of the new "friendly" relationship that high performance repeaters have achieved, T-Mobile USA now sell the Nextivity repeaters to end users.

Nokia

Nokia's primary business focuses on infrastructure for the macro layer, but the company has jumped into the small cell game as well. They have announced small cell relationships with T-Mobile and Avantel (Colombia), but in general Nokia has been more successful in outdoor deployment than with indoor small cells. Nokia has integrated a Ruckus Wi-Fi AP into their indoor small cell product line, to fill out the critical need for unlicensed operation. With the completion of its Alcatel-Lucent acquisition, Nokia has rationalized its small cell portfolio. It has kept the residentia/SOHO femtocell product line based on Qualcomm SoC. Its other indoor and outdoor small cells are based on its macro platform. With the common hardware and software stack, Nokia is able to scale up/down LTE features to address a wide range of small cell market segments from high-power outdoor units down to low power Remote Radio Heads.

OpenCell

Based in the UK, OpenCell provides indoor mobile infrastructure as a managed service. The company targets small enterprises less than 50,000 square foot with Enterprise Femtocells. The company has established interconnection arrangement with major UK operators and provides a complete turnkey solution to enterprises, from design, installation and management.

Ruckus Wireless (to be acquired by ARRIS)

Ruckus Wireless uses adaptive antenna technology to deploy high-capacity, interference resistant Wi-Fi access points, and has focused on Wi-Fi offload for carriers such as PCW and KDDI. The company has partnered with Nokia for converged licensed/unlicensed small cells, and collaborated with Alcatel-Lucent on Licensed Wi-Fi Aggregation (LWA) which allows aggregation between LTE channels and Wi-Fi channels without forcing the LTE waveform into the Wi-Fi spectrum. Most recently, the company announced its OpenG technology initiative (based on 3.5 GHz CBRS) to provide cellular coverage and capacity indoors by leveraging shared spectrum for neutral host capable small cells. The company will find a new "home" after a series of merger announcements in the past year. Last year, Brocade, a networking company, acquired Ruckus as a part of its wireless strategy. A few months later, Broadcom announced its plan to acquire Brocade for Brocade's fiber channel storage area networking business. As a part of this complicated deal, Broadcom has agreed to sell Ruckus, and a part of Brocade's switching and routing business, to ARRIS. So, Ruckus will now be part of ARRIS, soon after the Broadcom-Brocade merger closes.

Samsung

Samsung has deployed millions of CDMA femtocells in North America, with both Sprint and Verizon Wireless using the Samsung "UbiCell" for initial deployments. Samsung also

supplied picocells for WiMAX networks so they have easily converted to LTE small cell products, which have been selected by Sprint and a few other operators for ongoing LTE deployment. Most recently, Samsung has partnered with Qualcomm to support LTE-U/LAA capable femtocells. Samsung has been a key infrastructure supplier for Reliance Jio's LTE rollout, and looks to expand its infrastructure business in North America with learnings from the Jio network buildout. Samsung has a portfolio of residential, enterprise, and carrier grade small cells along with its macro product line used in the Jio rollout.

SerComm

Sercomm offers residential and enterprise small cells as well as Wi-Fi routers as a Taiwanese ODM. The company has taken the obvious step of integrating their Wi-Fi router and femtocell products together. Recently the company has focused on China and TD-LTE applications, and supplies TD-LTE, FDD-LTE, and dual mode TDSCDMA/TD-LTE small cells to that market. The company has also developed CBRS-capable small cell for the North American market.

SOLiD Technologies

SOLiD developed fiber optic DAS and remote radio head products over a period of 12 years in Korea, and has grown quickly in the American market. The company has fiber-based indoor DAS systems as well as high-power radio units (20W) for outdoor applications. The company has patented WDM fiber solutions which give them an advantage in fiber efficiency, especially for complex DAS installations. SOLiD has gained some market share in the enterprise space for DAS systems, integrating the optical and wireless networks in a flexible way because they do not push a particular form of fiber or cable. The company earlier this year acquired its exclusive N. American sales, marketing, and support partner, REACH Holdings to further expand in the region.

Spidercloud Wireless

SpiderCloud has been very successful converting their field trial and early deployments into major customer wins with Vodafone, Verizon, and America Movil. The company is seen as a major player in the enterprise segment with expanding product features and spectrum bands, including LTE-U/LAA, CBRS, MulteFire, etc. The company is focused on enterprise networks, using a centralized controller to coordinate both Wi-Fi and licensed/unlicensed/shared LTE radio nodes. The company has established a key partnership with Cisco, where they work together to outfit the Cisco Wi-Fi APs in the field with "plug-in" modules, and also where Cisco sells the SpiderCloud solution for enterprise opportunities. The company continuous to expand its strategic partnerships with leading infrastructure vendors and mobile operator partnerships for sell-through.

Surecall

Surecall provides repeaters in the US market, with a focus on enterprise applications. The company has FCC certified products for enterprise, home, and automotive applications and has achieved significant deployments in corporate and college campus scenarios and continues to see robust demand for its products and is expanding its distribution partnerships including its most recent one with Authorized Integrators Network (AiN) group.

Westell

Westell offers DAS equipment, TMAs, electrical support equipment, and services for operators engaging in the in-building market. The company acquired Cellular Specialties, Inc. in 2014. The company has stopped its latest DAS development project and is in the midst of major reorganization.

Wilson Electronics (WeBoost)

Wilson Electronics operated for years as the largest, and arguably, the most legitimate of the unauthorized cellular repeater suppliers in North America. Wilson was involved in the repeater industry's effort to be FCC "authorized", and has now achieved FCC certification for their consumer products, with the majority of revenue shifting over to certified products during 2014. Wilson has a large network of dealers/installers in the US market. The company acquired zBoost in early 2015 as a "value" product line, while its branded WeBoost act as a "premium" class product. It also has a product line called Wilson Pro targeting the enterprise segment.

Zinwave

Focused on indoor DAS applications, Zinwave has established a growing customer base with vertical markets in Europe, and is looking to expand internationally in the USA and Asia. The company uses a combination of optical and passive DAS with primary and secondary hubs to distribute signals cost-effectively. Zinwave was acquired by McWane Inc., a diversified manufacturing company, in 2014, and has established its headquarter in Dallas, Texas. Focused on indoor DAS applications, Zinwave has established a customer base with vertical markets in Europe, Australia, and an interesting casino in Macao. Zinwave partners with Edgewater Wireless for Wi-Fi implementation.

ZTE:

ZTE offers a complete line of small cell products, and should be considered a major contender for the "nanocell" tender in late 2015. The company has been commercially shipping femtocells to Starhub in Singapore since 2009. The company also recently touted Qcell (DRS architecture) solution win at China Telecom. The ZTE product line is based on

software-defined radios based on Texas Instruments SoCs which have the horsepower to run macro-level software for ideal coordination in a multimode HetNet.

10 ACRONYMS

2G: Second Generation Cellular

3G: Third Generation Cellular

3GPP: Third Generation Partnership Project

4G: Fourth Generation Cellular

AP: Access Point (often referring to Wi-Fi access point)

ARPU: Average Revenue Per User

BSC: Base Station Controller

BTS: Base Transceiver Station

Bits/Hz/sec: Digital bits transmitted per Hertz of bandwidth per second

CA: Carrier Aggregation

CAT-5: Category 5 Ethernet cable

CBRS: Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US

CDMA: Code Domain Multiple Access, a 2G radio interface

CoMP: Coordinated MultiPoint

CPE: Cost per Enplaned Passenger, a financial metric for airports that reflects all airline payments for use of an airport

CPRI: Common Public Radio Interface, a non-profit organization and interface format

CPU: Central Processing Unit

DAS: Distributed Antenna System

dBm: Decibels of power relative to 1mW

DRS: Distributed Radio System, a form of single-operator RRH (e.g., Ericsson Radio Dot, Huawei's LampSite)

DSL: Digital Subscriber Line

eICIC: Enhanced Inter-Cell Interference Coordination

EMEA: Europe, Middle East and Africa

eNB: e Node B, or the radio access node for LTE

FDD: Frequency Division Duplexed

GAA: General Authorized Access, applicable for the 3.5GHz shared spectrum, the lowest priority access, similar to unlicensed spectrum use

GB: Gigabyte

Gbps/km2: Gigabits per second per square kilometer

GHz: Gigahertz

GkM: Gbps per square kilometer per MHz, a traffic density gauge

GSM: Global System for Mobile communications, a 2G radio interface

GW: Gateway (normally referring to a femto gateway)

HetNet: Heterogeneous Network

HSPA: High Speed Packet Access

HSPA+: A subsequent evolution of HSPA with higher throughput

Hz: Hertz (cycles per second)

IDAS: Indoor Distributed Antenna System

IoT: Internet of Things

I-ub: Interface standard for base stations

I-uh: Interface standard for femtocell to serving gateway

Km: Kilometer

LAN: Local Access Network

LTE: Long Term Evolution, a "4G" radio interface based on orthogonal frequency division multiplexed data

LTE-A: LTE Advanced, a higher bandwidth version of LTE

LAA: LTE-License Assisted Access, a 3GPP-compliant "official" LTE-U technology

LTE-U: LTE-Unlicensed, an "unofficial" technology to run LTE waveform on 5GHz unlicensed spectrum band

MOCN: Multi-Operator Core Network, a network sharing method at a core network level

MORAN: Multi-Operator Radio Access Network, a network sharing method at a radio network level

OBSAI: Open Base Station Architecture Initiative, a non-profit organization and interface format

OEM: Original Equipment Manufacturer

MAC: Media Access Control layer

MHz: Megahertz

MkM: Mbps per square kilometer per MHz

MIMO: Multiple Input, Multiple Output

MS: Mobile Station

mW: Milliwatt

OBSAI: Open Base Station Architecture Initiative

O-DAS: Outdoor Distributed Antenna System

OEM: Original Equipment Manufacturer

OFDM: Orthogonal Frequency Division Multiplexed

OTA: Over the Air

node B: A radio base station for WCDMA/HSPA

PAL: Priority Access License, applicable for the 3.5GHz band, second highest priority in use of the 3.5GHz shared spectrum

PC: Personal Computer

QoS: Quality of Service

RAN: Radio Access Network

RF: Radio Frequency

RNC: Radio Network Controller

RRH: Remote Radio Head

SAS: Spectrum Access System, a software system to coordinate spectrum sharing (although it can be applied across all shared spectrum, its use is primarily focused on 3.5GHz CBRS)

SIP: Session Initiation Protocol

SNR: Signal-to-Noise Ratio

TB: Terabyte (1000 GB)

TD-LTE: Time Domain based Long Term Evolution

TD-SCDMA: Time Domain Synchronous Code Domain Multiple Access

TV: Television

UE: User Equipment

VAR: Value Added Reseller

W: Watts

WCDMA: Wideband Code Domain Multiple Access, a 3G radio interface

Wi-Fi: Wireless Fidelity (802.11 data communications)

11 METHODOLOGY

Mobile Experts combined the forecasts from five separate market areas in this overall in-building market study. We based the quantitative forecast on our deep-dive publications in each specific area:

- *Global DAS Market*, September 2016 (forecast updated April 2017)
- *Small Cells 2017* (March 2017)
- *CRAN and VRAN 2016: Centralization and Virtualization* (April 2016)
- *Carrier Wi-Fi and LTE-U*, October 2016
- Plus independent market analysis of Repeaters

In this analysis, we emphasized the economic analysis of various options against each other. We examined multiple case studies to ascertain the most cost-effective alternative for the mobile operator, for the neutral host, and for the enterprise. We have based our balanced forecasts on these comparisons, by estimating how many decision-makers in each group will influence a chunk of the market.

Finally, we interviewed multiple building owners and system integrators to understand the trend toward infrastructure purchases by the enterprises themselves. We conducted interviews related to each vertical market in order to understand the relevant factors and the likelihood of growth.

In each of our individual market studies, Mobile Experts interviews at least 20-30 mobile operators, and compares the top-down input received from operators with the bottom-up inputs from OEMs and semiconductor suppliers. The key element in most Mobile Experts forecasts is simple: If we don't see demand from the operators showing up at the semiconductor level, then it's not real.

In this comparative study, Mobile Experts focused exclusively on the indoor mobile infrastructure options that support enterprise applications. We have taken each technology area (DAS, Small Cell, DRS, Repeater), and evaluated how many in-building radio nodes are used to support an enterprise, and how many are used for the carrier's general public coverage. We then broke down each radio solution to understand how many units will be purchased by the enterprise and deployed by the enterprise, to illustrate the changing business model.

This report simplifies the forecast by focusing only on radio shipments. Full coverage of revenue, pricing, and market shares can be found in the full Mobile Experts market studies.

Definitions	Description
DAS	A network of radio nodes for mobile communications, using a simulcast of identical RF waveforms from a hub.
Heavy DAS	DAS with multiple bands for multiple operators
Light DAS	DAS with a single band for multiple operators (or for a single operator)
Multioperator	DAS systems configured to allow multiple mobile service providers to use the same distribution and radio nodes.
Small Cell	Network nodes which transmit less than 30W of composite power per sector, which include baseband processing for complete enodeB/nodeB/BTS functionality.
Femtocell	The term "femtocell" refers to a residential/SOHO unit which works autonomously without much coordination and handover to the macro network
DRS	Distributed Radio Systems use twisted-pair cables to distribute radio signals to various antenna nodes in a building, with a central remote radio head to process the radio signals. Radio Dot uses RF over twisted pair. LampSite uses I/Q samples over twisted pair. Both examples are listed in the Mobile Experts category for RRH, but we count the number of DRS nodes in this report to illustrate the coverage of these systems.
Low Power RRH	A Remote Radio Head which connects to a macro base station baseband processing center via digital I/Q interface, typically over optical fiber. Unless designated as a "Split Baseband RRH", an RRH uses CPRI or a similar interface between PHY baseband and RF. A Low Power RRH transmits less than 300 mW for indoor applications.
Split Baseband Low Power RRH	A Remote Radio Head which connects to a macro base station baseband processing center via digital I/Q interface, typically over optical fiber. A Split-Baseband RRH includes some baseband processing, normally in the PHY and MAC areas, but with other baseband processing located centrally. A Low Power RRH transmits less than 300 mW for indoor applications.
IDAS	Indoor DAS, transmitting less than 10W of composite power per node. Note that some low-power nodes will be physically outdoors but are still categorized as "indoor" based on power level.
Repeater	A radio receiver and transmitter which boosts the bi-directional signal power for a local user without higher level baseband processing
Broadband Repeater	A broadband repeater generally receives and retransmits all of the RF signals within a given band (multiple operators). These units are generally sold on the "gray market" because they are generally not authorized by mobile operators.
Carrier Specific Repeater	A repeater endorsed by mobile operators, which generally use filters and DSP to isolate the signals for a specific mobile service. The unit can be purchased either by the operator or by an enterprise but is endorsed by the operator.
Relay	An LTE radio node which demodulates and remodulates the signal to allow for higher order modulation within a building
Single-band Relay	An LTE relay which receives and re-transmits in the same LTE band.
Cross-band Relay	An LTE relay with a link to the macro network in one band, and a link to the end user on a second LTE band.

Figure 21. Key definitions for terms